
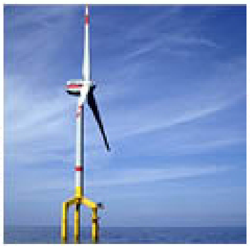


Assessment of Offshore Wind Energy Leasing Areas for the BOEM New Jersey Wind Energy Area

W. Musial, D. Elliott, J. Fields, Z. Parker, G. Scott, and C. Draxl
National Renewable Energy Laboratory

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-5000-60403
October 2013

Contract No. DE-AC36-08GO28308

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Executive Summary

The National Renewable Energy Laboratory (NREL), under an interagency agreement with the U.S. Department of the Interior's 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 development and evaluation of the delineations for the New Jersey (NJ) WEA.

The overarching objective of this study is to develop a logical process by which the New Jersey WEA can be subdivided into non-overlapping leasing areas for BOEM's use in developing an auction process in a renewable energy lease sale. NREL identified a selection of leasing areas and proposed delineation boundaries within the established NJ WEA. The primary output of the interagency agreement is this report, which documents the methodology, including key variables and assumptions, by which the leasing areas were identified and delineated.

As part of the evaluation, NREL researchers:

1. Developed a preliminary process and criteria to create three to five leasing areas within the original BOEM NJ WEA.
2. Presented their methodology for analysis and technical approach at a New Jersey renewable energy task force meeting on December 18, 2012 (Musial and Elliott 2012).
3. Reviewed and assessed the proposed development parameters provided in 11 responses to the 2011 New Jersey Call for Information and Nominations.
4. Revised the methodology for a modified NJ WEA, hereafter called the New Jersey area of analysis (developed by BOEM) to address feedback from the New Jersey Board of Public Utilities (BPU), U.S. Coast Guard, and other task force reviewers.
5. Identified three options for delineating the NJ area of analysis (Figure ES1) into two, three, and four leasing areas, respectively, and conducted analyses to compare and evaluate the different delineation scenarios.
6. Performed further analyses for the four leasing area delineation options on the effect of different turbine spacing scenarios on the wake losses and development potential.
7. Evaluated potential development scenarios using 500-megawatt (MW)-unit wind plants and evaluated the wake effects for a single wind facility versus full development (500-MW wind plants in all four leasing areas) for different spacing scenarios.
8. Prepared this report summarizing the NREL technical approach and final recommendations to BOEM for leasing area delineations within the NJ area of analysis and the effects of different turbine spacing scenarios on potential development and energy production.

In addition, NREL considered information from the following sources:

- The New Jersey Call for Information and Nominations (the "Call") and 11 responses to the Call
- Presentations delivered at the New Jersey Renewable Energy Task Force meeting held on December 18, 2012
- The modified area of analysis that was developed by BOEM to address potential development area constrictions for the delineation analysis
- Verbal input received from a conference call on May 30, 2013, with BOEM, BPU, and Rutgers University
- The report: *An Advanced Atmospheric/Ocean Assessment Program Designed to Reduce the Risks Associated with Offshore Wind Energy Development Defined by the NJ Energy Master Plan and the NJ Offshore Wind Energy Economic Development Act,* prepared by Rutgers University for the BPU (Glenn and Dunk 2013)
- Available information (including websites and project reports) on turbine density and array spacing used in European and U.S. offshore wind power projects.

As a result of discussions at the New Jersey Renewable Energy Task Force meeting on December 18, 2012, BOEM revised the original NJ WEA that was described in the 2011 Call for Information and Nominations and provided the revised area to NREL. Additionally, recognizing that existing subsea cables within the area of analysis could pose micro-siting issues, BOEM asked NREL to assume that any aliquots containing active subsea cables would not be available for the installation of wind turbines. It is important to note that the exclusion of the known cabling area is only for the purpose of this analysis but does not reflect a decision on the part of BOEM to exclude the area from leasing or development consideration at this time.

NREL developed and evaluated three different delineation options for two, three, and four leasing areas, respectively. The decision to not consider the fifth leasing area option, which was part of NREL's preliminary analysis plan (Musial and Elliott 2012), was based on joint discussions between the NJ BPU and BOEM. For each of the delineation options, several quantitative evaluation criteria were examined and other qualitative criteria were considered. These criteria are listed in Table ES1.

This study concludes that a delineation strategy using mostly northwest-southeast diagonal delineation lines is optimal for maximizing developable area, balancing bathymetry concerns, and providing coastal access for export cables as well as construction and service vessels. In some of the delineations, balancing these factors resulted in delineation lines that were a combination of straight west-east and diagonal northwest-southeast lines. The three delineation options are shown in Figure ES1. The green-shaded cells in the northern part of the area of analysis are aliquots that contain active subsea cables which were excluded from wind turbine development in this report.

Table ES1. Evaluation Criteria Used by NREL to Assess the New Jersey Area of Analysis
(Source: NREL)

Quantitative Evaluation Criteria	Qualitative Evaluation Criteria
Total area [square kilometers (km^2) and acres]	Distance from shore
Potential installed capacity [megawatts (MW)]	Technology challenges
Bathymetry [meters (m)]	Development cost
Annual average wind resource [meters per second (m/s)]	
Gross capacity factor (%)	
Wake losses (%)	
Array orientation angle (degrees)	
Turbine spacing within array [rotor diameters (D)]	
Capacity factor after wake losses (%)	
Annual energy production [gigawatt-hours (GWh)]	

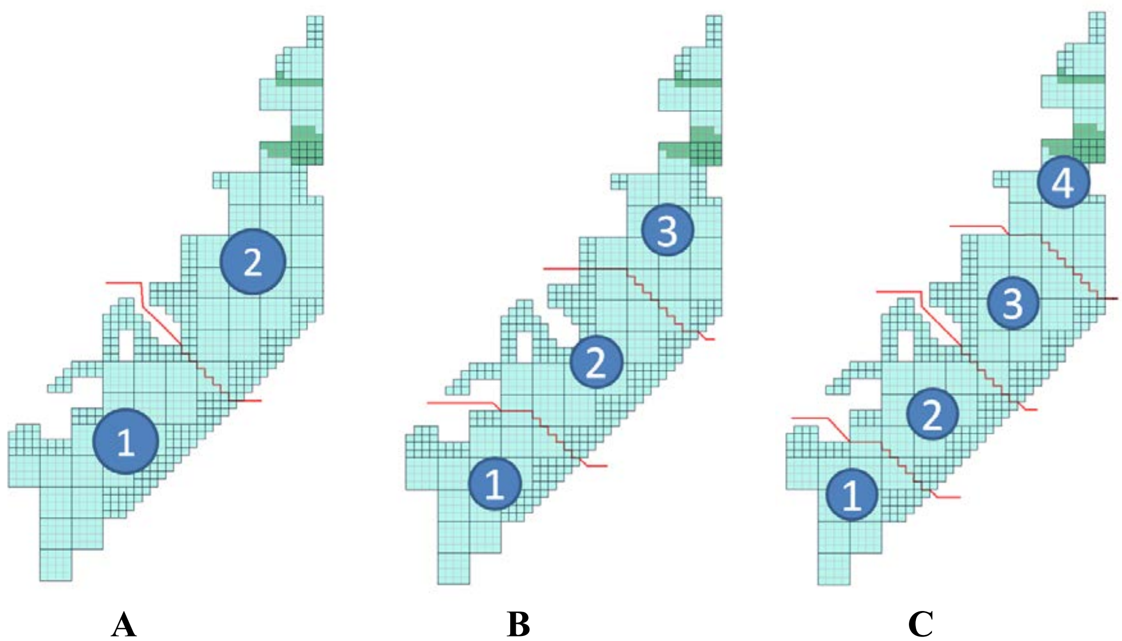

Figure ES1. NJ area of analysis leasing area delineation options developed and evaluated by NREL: (A) two leasing areas, (B) three leasing areas, and (C) four leasing areas. These options provide reasonable delineation scenarios for the NJ area of analysis.
(Source: NREL)

Table ES2 provides a comparison of the quantitative results for the three different delineation options assessed by NREL for the NJ area of analysis in Figure ES1. Much of the analysis was conducted with the AWS Truepower OpenWind Enterprise tool (AWS Truepower 2012). Wind turbine array modeling was based on the NREL 5-MW reference turbine (Jonkman et al. 2009) which has a 126-m diameter rotor.

Table ES2. New Jersey Analysis for Three Different Delineation Options and 10 D x 12 D Turbine Spacing
(Source: NREL)

	Two Leasing Area Delineation		Three Leasing Area Delineation			Four Leasing Area Delineation			
Parameter	Leasing Area 1	Leasing Area 2	Leasing Area 1	Leasing Area 2	Leasing Area 3	Leasing Area 1	Leasing Area 2	Leasing Area 3	Leasing Area 4
Total area (km^2)	640.8	679.68	383.04	518.4	442.08	276.48	372.96	397.44	298.08
Total area (1000 acres)	158.35	167.95	94.65	128.1	109.24	68.32	92.16	98.21	73.66
Average depth (m)	24	25	25	24	24	25	24	26	24
Bathymetry – depth range (m)	16-38	17-34	16-37	16-34	17-35	15-38	16-34	17-34	17-32
Average wind speed at 90 m (m/s)	8.4	8.6	8.4	8.5	8.6	8.4	8.4	8.5	8.6
10D x 12D - 75 degree Grid									
Gross capacity factor (CF) (%)	45.4	46.5	45.4	45.7	46.8	45.4	45.4	46.1	47
Potential capacity (MW)	1660	1780	945	1185	1075	665	850	890	690
Wake losses (%)	8.9	9.1	8.1	9.5	7.9	7.3	9.2	9.6	6.9
Gross CF after wake losses (%)	41.3	42.3	41.7	41.3	43.1	42.1	41.2	41.7	43.7
Annual Energy Production (GWh)	6016	6597	3455	4293	4062	2451	3072	3252	2644

Each option was assessed for a baseline wind turbine array spacing in rotor diameters (D) which was chosen to be 10 D x 12 D, with the 12 D spacing aligned with the predominant prevailing wind direction. This spacing is representative of many of the proposals that were submitted to BOEM under the NJ Call. The Call responses indicated significantly lower turbine array densities and wider spacing for the proposed NJ offshore projects than those in large offshore projects currently in operation or under construction (Figure ES2). The turbine spacing proposed in the Call ranged from a minimum of 7 D x 10 D to a maximum of 15 D x 15 D, corresponding to a range of turbine array densities from 1.4 to 4.6 MW/km^2 and a mean value of 3.0 MW/km^2 (about 10 D x 11 D)—based on information available from nine of the nominations. This compares to a range of 3.5 to 8.8 MW/km^2 and a mean of 6.0 MW/km^2 for existing and under construction projects, which have significantly higher densities than both the 2.6 MW/km^2 for the baseline 10 D x 12 D spacing and the Call nominations. In addition, the industry array density data show no obvious trends that could help predict future array densities.

Cable costs are an important factor that constrains turbine spacing. The optimum array density must be assessed taking in to account many variables including wake losses, bottom conditions, distance to shore, competing use issues as well as cable cost. Although wider turbine spacing reduces wake losses and potentially reduces turbine maintenance costs, it increases cable costs and other costs associated with development. This may be the reason that wider spacing is not being adopted as aggressively as the NJ Call responses would indicate. However, a full analysis of the cable costs is beyond the scope of this study.

As shown in Table ES2, the analysis covered a wide range of variables but focused on the area's physical characteristics, and how they might affect the development potential of one leasing area relative to the others. In the three (Figure ES1-B) and four (Figure ES1-C) leasing area delineation options, the wake losses were significantly higher in the middle areas than for the end leasing areas. These wake losses ranged from 9.2% to 9.6% in the middle leasing areas and 6.9% to 8.1% in the end leasing areas for the three and four leasing area options when the leasing areas were filled to maximum capacity. As a key part of the delineation strategy, NREL increased the size of the middle leasing areas compared to the outer areas to compensate for the higher wake losses. The increased size would provide developers in middle leasing areas with more flexibility to build internal buffers. In all three options in Figure ES1, all leasing areas have a maximum development potential greater than 500 MW, ranging from more than 1,600 MW gross development capacity for the two leasing area option to more than 600 MW for the four leasing area option.

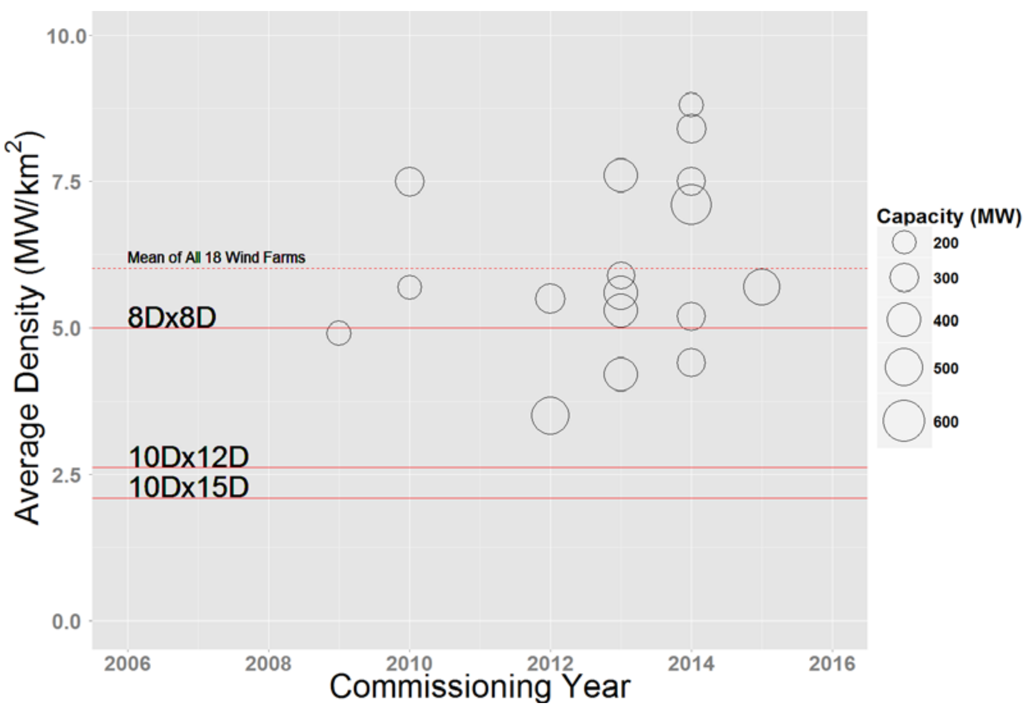

Figure ES2. Average turbine array density for 18 large (>200 MW capacity) offshore wind power projects. Solid red lines indicate the array density for the spacing scenarios used by NREL in the New Jersey assessment
(Source: NREL)

Annual average wind speeds, as shown in Figure ES3, vary from about 8.3 meters per second (m/s) to 8.7 m/s across the area of analysis. These winds are highest in the northeast part of the area and lowest along the western fringes, especially in the south. The prevailing winds, indicated by the wind rose shown in Figure ES3, are from the southwest directions. Therefore, the southernmost leasing area generally has the best exposure to the prevailing winds from the southwest directions, whereas the northernmost leasing area has the highest average wind resource. Gross capacity factors (before wake losses) are highest in the northernmost leasing areas, varying from 46.5% to 47%, and lowest in the southern leasing areas averaging 45.4%. However, gross capacity factors after wake losses are lowest in the middle leasing areas. The northernmost leasing areas still have the highest capacity factors after wake losses.

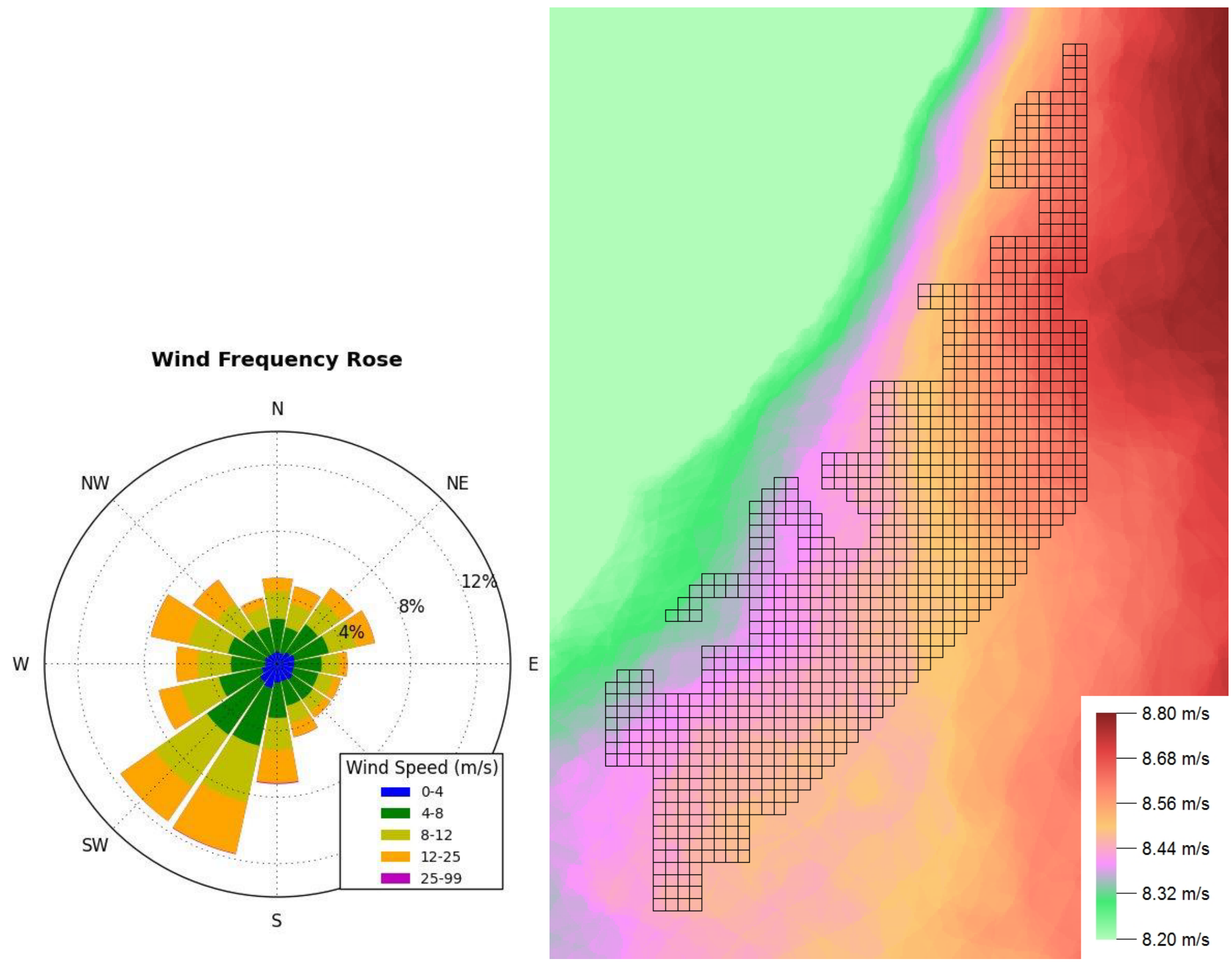

Figure ES3. The NJ area of analysis showing the annual average wind speed in 0.12 m/s increments and the wind frequency rose with prevailing winds from the southwest direction
(Source: NREL)

The water depth, or bathymetry, map in Figure ES4 shows that shallow waters less than 30 m deep (areas shaded in blue colors) are prevalent over most of the area. Deeper water (30 m and greater) (purple colors) is located near the eastern edges of the area, with some patches near the geographic center. Table ES2 includes estimates of average water depth and the range of water depth for each leasing area. The deep water above 30 m represents less than 10% of the total capacity in most of the leasing areas. Therefore, most of the areas would not be affected significantly by the water depth in terms of the cost and development challenges imposed by deep water.

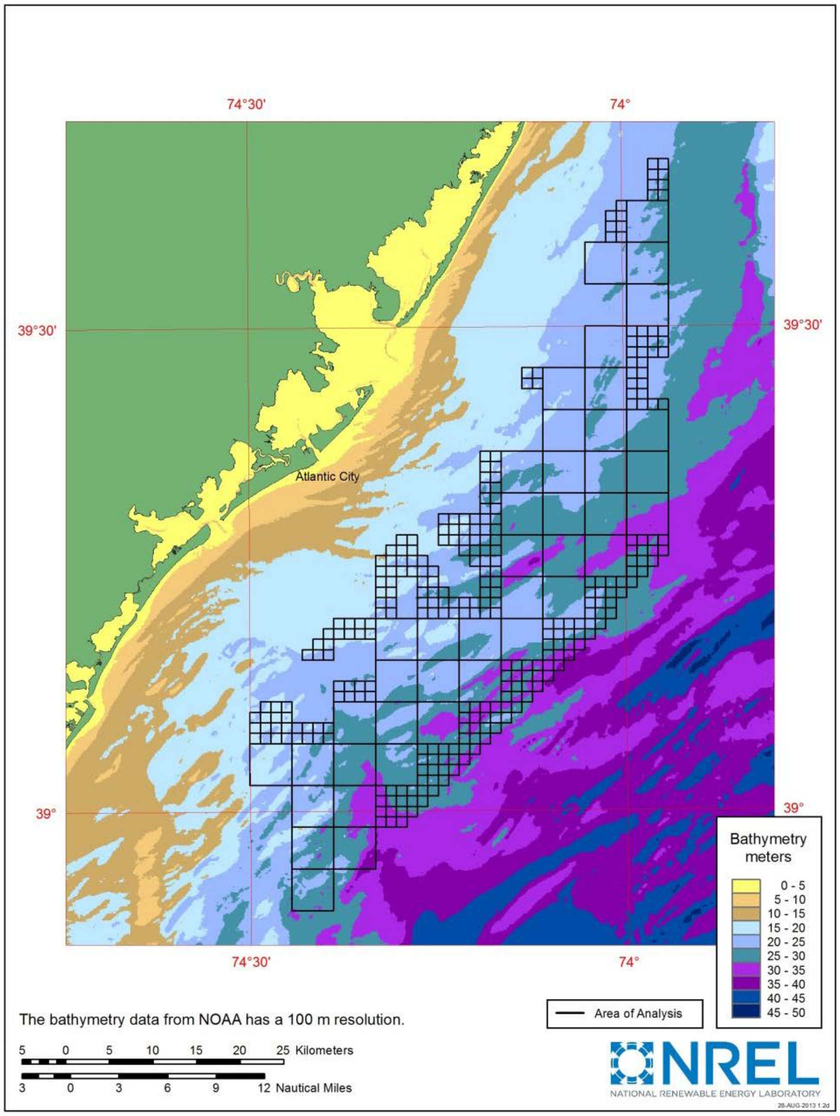

Figure ES4. Water depth map for the New Jersey area of analysis
(Source: NREL)

For the four leasing area delineation (in option C), NREL performed additional analyses and comparisons to assess the effects of different wind turbine spacing on wake losses, development potential, and annual energy production. Although these additional analyses were not performed for the two and three leasing area delineations, the results from the four leasing area delineation can provide insight on the effects of wind turbine spacing for the other delineations. The report provides results of the modeling and analysis for the following four scenarios:

- 10 D x 12 D baseline spacing
- 8 D x 8 D spacing, (Represents NREL's estimates of gross wind potential for the United States and is comparable to the spacing used in large offshore wind projects (Figure ES2)
- 10 D x 15 D spacing (Represents wider spacing than proposed in most Call nominations)
- 500 MW at 10 D x 12 D and 8 D x 8 D spacing in each leasing area for: 1) each wind facility by itself (no other developments in the area of analysis), and 2) in the presence of the other three projects (500 MW developed in each of the four leasing areas). This shows how external wakes from neighboring projects contribute to the total losses within a given project (see Section 4.7).

NREL researchers evaluated the maximum development capacity of each leasing area by creating turbine layouts that maximized the number of turbines in each leasing area by using the NREL 5-MW reference turbine in the different gridded turbine array spacing scenarios. In creating these layouts, it was assumed that the developers of each leasing area would impose an internal setback of at least 8 D from either side of a delineation internal boundary, anticipating that the neighboring developer could feasibly place turbines near the boundary. Example layout maps with a setback buffer along the delineation line are shown in Figure ES5 for two different spacing scenarios in the four leasing area delineation.

Figure ES5. New Jersey area of analysis and layout maps of the four leasing area delineation for the 8 D x 8 D spacing with a zero-degree grid orientation (left) and 10 D x 12 D baseline spacing with a 75-degree grid orientation (right)
(Source: NREL)

Table ES3 shows the results of the full development of wind turbines in all four leasing areas for the different spacing scenarios and projects limited to a 500-MW capacity. Estimates of the potential capacity for the 8 D x 8 D spacing in each of the four leasing areas are approximately twice that for the 10 D x 12 D spacing because of higher turbine array density. The potential capacity across the four leasing areas ranges from 1,320 MW to 1,760 MW for the 8 D x 8 D spacing and from 665 MW to 890 MW for the 10 D x 12 D spacing. However, wake losses are significantly higher for the 8 D x 8 D spacing (10.8% to 13.9%) compared to the 10 D x 12 D spacing (6.9% to 9.6%). The highest wake losses in both spacing scenarios occur in the middle leasing areas.

For the 10 D x 15 D spacing, the potential capacity ranges from 525 MW to 720 MW and is approximately 20% less than the 10 D x 12 D baseline spacing. Wake losses range from 6% to 8.5% and are slightly less than losses for the 10 D x 12 D spacing.

The 500 MW siting scenarios were included to provide a more realistic estimation of wake losses since it is expected that a developer would retain some available area for buffers and to provide flexibility in siting. When the project size was limited to 500 MW in each leasing area, overall wake losses were significantly reduced (as compared to full development) by an average of 20% for the 10 D x 12 D spacing and 40% for the 8 D x 8 D spacing. Similarly, wake losses for the area of analysis average 6.6% for the 10 D x 12 D spacing and 7.3% for the 8 D x 8 D spacing. Thus, in the 500 MW project analyses, wake losses are only slightly higher for the 8 D x 8 D spacing than for the 10 D x 12 D spacing, and the annual energy production for the 8 D x 8 D spacing is only 1% to 2% less than that for the 10 D x 12 D spacing. However, the 500 MW 8 D x 8 D project occupies only about half the area as the 500 MW 10 D x 12 D project.

Table ES3. New Jersey Analysis for the Four Leasing Area Delineation with a Comparison of Different Spacing and Development Options
(Source: NREL)

Parameter	Four Leasing Area Delineation			
	Leasing Area 1	Leasing Area 2	Leasing Area 3	Leasing Area 4
Total area (km^2)	276.48	372.96	397.44	296.64
Total area (1000 acres)	68.32	92.16	98.21	73.3
Average depth (m)	25	24	26	24
Bathymetry – depth range (m)	15-38	16-34	17-34	17-32
Average wind speed at 90 m (m/s)	8.4	8.4	8.5	8.6
8D x 8D - 0 degree Grid				
Wake losses (%)	11.2	13.4	13.9	10.8
Gross capacity factor (CF) (%)	45.4	45.4	46.1	47.0
Gross CF after wake losses (%)	40.3	39.3	39.7	41.9
Potential capacity (MW)	1,320	1,630	1,760	1,405
Annual Energy Production (GWh)	4,660	5,618	6,128	5,162
10D x 12D - 75 degree Grid				
Wake losses (%)	7.3	9.2	9.6	6.9
Gross capacity factor (CF) (%)	45.4	45.4	46.1	46.9
Gross CF after wake losses (%)	42.1	41.2	41.7	43.7
Potential capacity (MW)	665	850	890	690
Annual Energy Production (GWh)	2451	3072	3252	2644
10D x 15D – 75 degree Grid				
Wake losses (%)	6.3	8.1	8.5	6
Gross capacity factor (CF) (%)	45.5	45.4	46.1	47.0
Gross CF after wake losses (%)	42.6	41.7	42.2	44.2
Potential capacity (MW)	525	685	720	555
Annual Energy Production (GWh)	1958	2507	2665	2148
8D x 8D – Limit 500 MW - 0 degree Grid				
Wake losses (%)	7.6	8.2	7.5	5.8
Gross capacity factor (CF) (%)	45.2	45.3	45.8	46.8
Gross CF after wake losses (%)	41.8	41.6	42.4	44.1
Potential capacity (MW)	500	500	500	500
Annual Energy Production (GWh)	1833	1823	1857	1934
10D x 12D – Limit 500 MW - 75 degree Grid				
Wake losses (%)	6.1	7.2	7.2	5.7
Gross capacity factor (CF) (%)	45.4	45.4	46.1	47.0
Gross CF after wake losses (%)	42.6	42.1	42.8	44.3
Potential capacity (MW)	500	500	500	500
Annual Energy Production (GWh)	1867	1844	1875	1940

Key Findings

Below are the key findings of the NREL analysis, and considerations for BOEM, policy makers, and stakeholders involved in the New Jersey offshore wind energy development process.

- The maximum capacity of the entire NJ area of analysis, using 10 D x 12 D spacing and internal buffers between leasing areas, was found to be between 3,100 MW and 3,400 MW, depending on the number of leasing areas. The NJ area of analysis is capable of supporting at least four leasing areas with equitable divisions using reasonable assumptions that would accommodate wind projects of at least 500 MW per area.
- Diagonal (roughly northwest-southeast) delineations proved to be the most efficient strategy for dividing the NJ area of analysis because they resulted in the shortest delineation boundaries which maximized the developable area. Higher potential wake losses in the middle leasing areas were compensated for by adding additional area to allow for greater flexibility when placing internal buffers.
- Bathymetry of the NJ area of analysis is generally favorable in all leasing areas and is not expected to alter the leasing value of one area relative to another. Most leasing areas would have over 90% of the water in depths less than 30 meters.
- Average annual wind speed for the NJ area of analysis ranged from 8.4 m/s to 8.6 m/s in all leasing areas assessed. This corresponds to a range of gross capacity factors between 45.4% and 47.0%.
- Total energy losses from wake effects in the fully developed baseline case of 10 D x 12 D spacing in all (four) leasing areas were reduced from a range of 7% to 10% to a range of 5% to 7% when project size was limited to 500 MW in each leasing area.
- The grid orientation angle was found to have only a minor impact on array efficiency using the OpenWind model with 10 D x 12 D spacing and 10% turbulence intensity. The best grid orientation angle was 75 degrees for the 10 D x 12 D spacing.
- Wake losses increased with decreasing turbine spacing. For the scenario of developing four leasing areas to their maximum potential, wake losses averaged 6%–9% for 10 D x 15 D spacing, 7%–10% for 10 D x 12 D spacing, and 11%–14% for 8 D x 8 D spacing. For all spacing scenarios, the highest wake losses were in the middle areas.
- If the projects were limited to 500 MW developed in all four leasing areas, wake losses were significantly reduced. The average wake losses for the area of analysis are 6.6% for 10 D x 12 D spacing and 7.3% for 8 D x 8 D spacing. However, the area required for an 8 D x 8 D project is only about half that for a 10 D x 12 D project.
- Wake effects from one leasing area to another will play a significant role in siting offshore wind turbines in the NJ area of analysis. However, NREL researchers found that wake losses from neighboring wind projects within the NJ area of analysis were less than 30% of the total array losses. Most wake losses are generated internally to a given project.
- The optimal number of leasing area delineations (i.e., two, three, or four leasing areas) may depend on requirements for development capacity or project size that may be dictated by

administrative or political policy. This report does not attempt to interpret potential constraints related to the New Jersey offshore wind legislation (New Jersey 2010).

- The four leasing area option provides ample development potential to allow for a commercial-scale project in each leasing area with a maximum potential for the greatest diversity of developers. More developers could result in more rapid concurrent development of the entire WEA.
- The wake analysis in this report is coarse by industry standards and it is recommended that prospective lessees investigate wake losses more rigorously before judging the values of these leasing areas. An 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 the 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 are appropriate for commercial offshore wind energy development, with a 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. On July 31, 2013, BOEM held the first of these competitive lease auctions for the Rhode Island/Massachusetts WEA (U.S. Department of the Interior 2013), and on September 4, 2013, for the Virginia WEA. 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 further analysis using engineering tools and available WEA site characteristics to ensure that the leasing areas are appropriately divided.

1.1 Summary of NREL 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 New Jersey, the interagency agreement work scope comprises several tasks to assist BOEM in making the final determination for delineating the New Jersey (NJ) WEA into leasing areas that are capable of supporting a commercially viable project. The expectation is that the proposed 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 relevant BOEM Federal Register Notices. NREL researchers, based on their expertise, were asked to consider and incorporate this information, as appropriate, into the leasing area identification and delineation methodology.

Second, NREL was asked to propose a methodology and identify the factors they used to delineate the number of leasing areas and their proposed boundaries. On December 18, 2012, NREL made a presentation to the New Jersey Renewable Energy Task Force to present their methodology (Musial and Elliott 2012). The presentation described the preliminary method for identifying and evaluating three to five potential leasing areas within the New Jersey WEA and performing an independent analysis on the different delineation options. As a result of discussions with other stakeholders at this New Jersey Renewable Energy Task Force meeting, BOEM removed the easternmost OCS blocks and aliquots in the original NJ WEA from leasing consideration due to vessel traffic concerns. In addition, BOEM suggested excluding known subsea cable routes that may pose development constraints. These changes effectively modified the NJ WEA and created a new area for analysis.

Following reviews of NREL's preliminary methodology and after receiving feedback from BOEM, the New Jersey Board of Public Utilities (BPU), and Rutgers University, NREL made some revisions to the methodology. These revisions included: 1) reducing the potential number of leasing areas to be evaluated from three to five areas down to two to four areas, 2) changing the wind turbine spacing and siting scenarios to significantly increase the turbine spacing for the baseline case and performing additional analyses not previously considered, and 3) re-evaluating the leasing area delineation strategies for the modified WEA. The reasons for most of these revisions were to address concerns raised by the NJ BPU and Rutgers University regarding the appropriate number of leasing areas and increasing the turbine spacing scenarios that were originally proposed by NREL. NREL researchers used this input, received through BOEM, to help guide the analysis and integrate the findings into this report.

Finally, NREL researchers will present the findings of this study to the BOEM New Jersey Renewable Energy Task Force upon the completion of the project.

1.2 New Jersey WEA and Leasing Areas

Since 2009, BOEM has been working with the BOEM New Jersey Renewable Energy Task Force to identify the most appropriate area for offshore leasing in New Jersey. This area was identified and published in a Call for Information and Nominations (hereafter referred to as the "Call") for wind power on the OCS offshore New Jersey in the Federal Register in April 2011. In response to the Call, BOEM received 11 nominations of interest wishing to obtain a commercial lease for wind energy. The NJ WEA described in the Call comprises 354,275 acres, or 1,433.7 square kilometers (km^2), and is shown in Figure 1. The WEA is intended to protect ecologically sensitive areas and minimize user conflicts while making an appropriate area available for commercial offshore wind energy development. BOEM intends to hold a lease sale to auction the NJ WEA and would like to issue leases that correspond to the entire identified WEA.

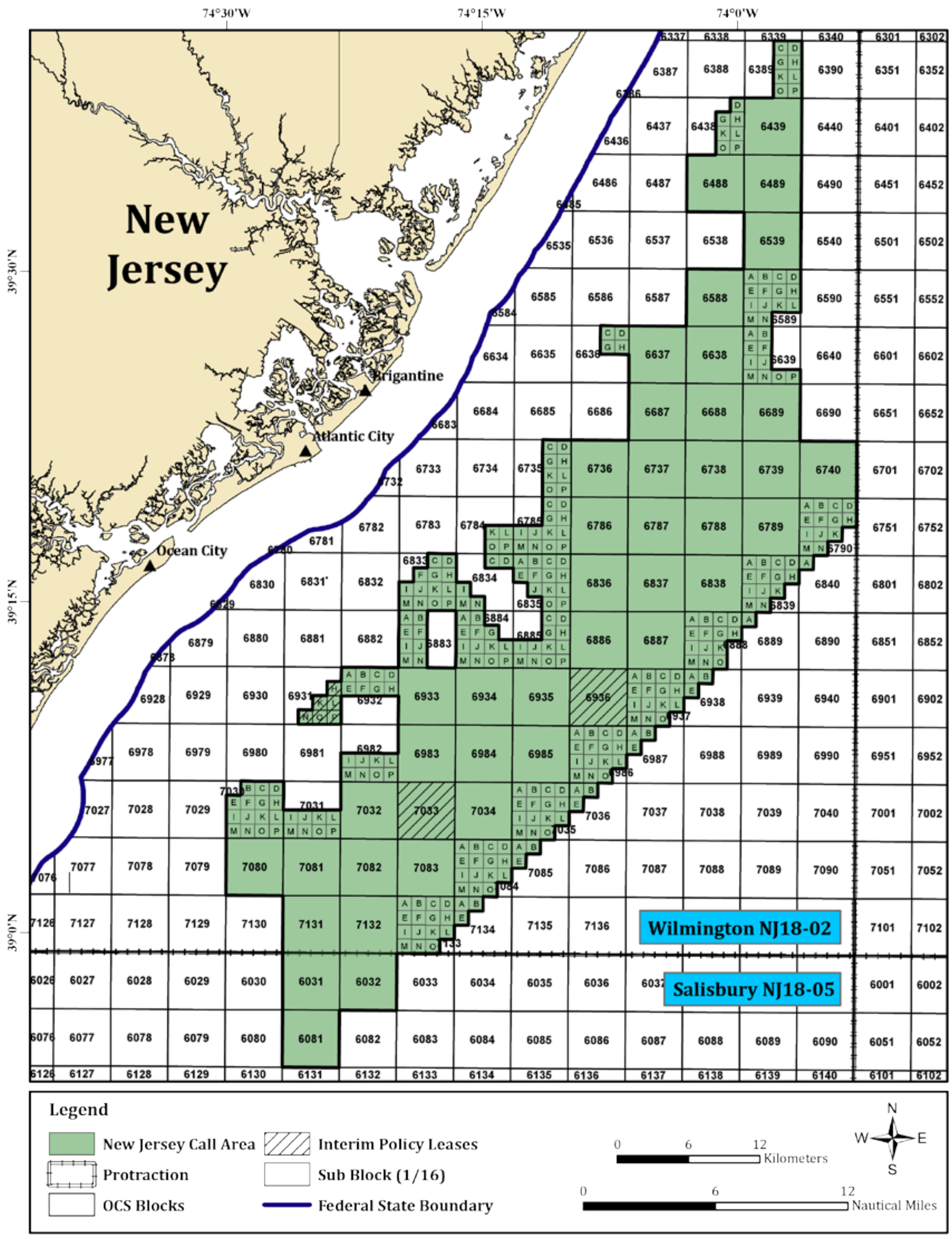


Figure 1. New Jersey Wind Energy Area used in the Call
(Source: BOEM)

As previously noted, NREL received a refined area of analysis for use in the assessment, hereafter referred to as the NJ area of analysis (shown in Figure 2).

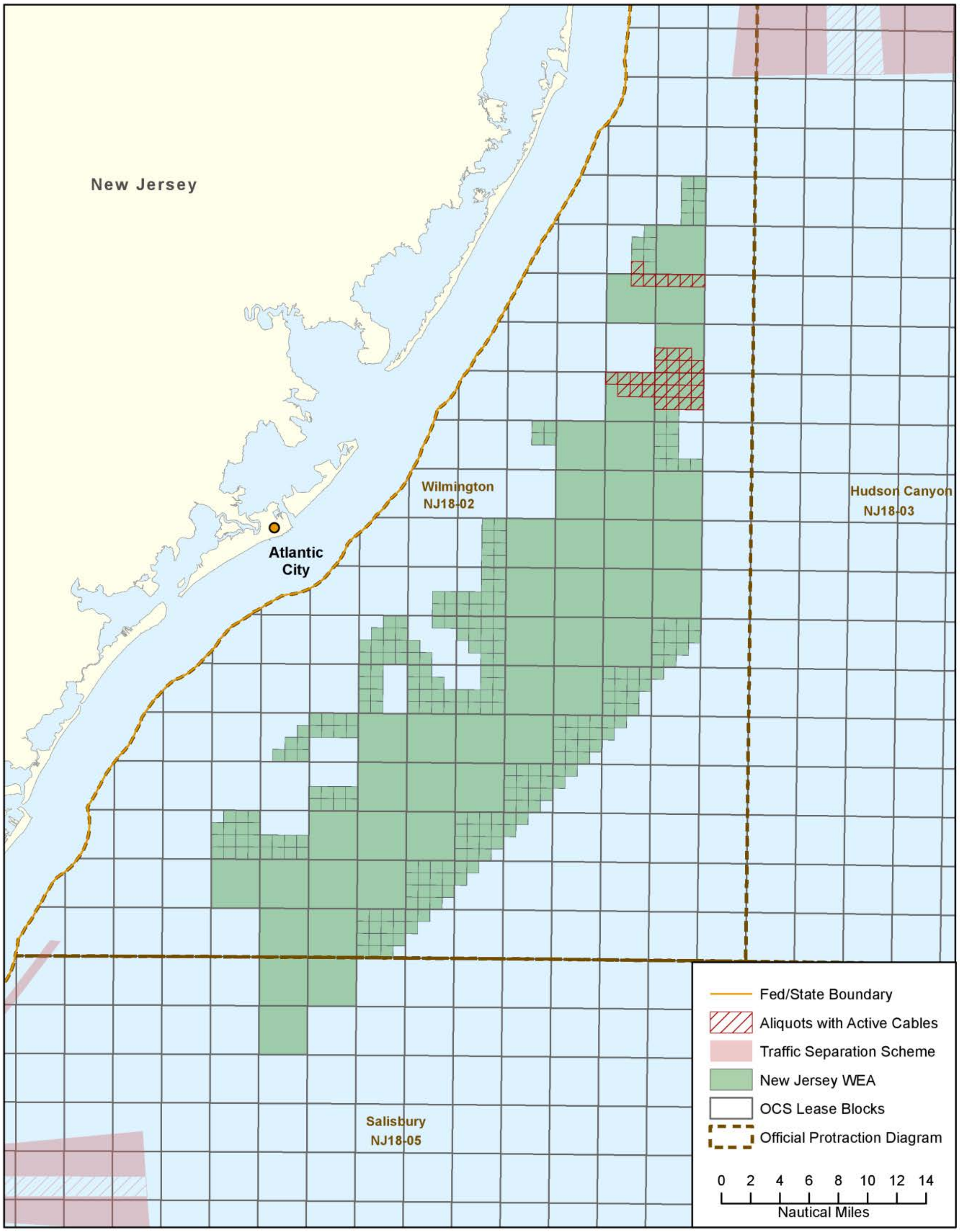


Figure 2. New Jersey area of analysis with easternmost aliquots removed for due to possible navigation concerns and northern aliquots removed (shaded areas) due to existing cables (exclusions for study only)
(Source: BOEM)

The area of analysis was developed by BOEM as a result of discussions at the New Jersey Renewable Energy Task Force meeting on December 18, 2012. There were two modifications to the NJ WEA to create the area of analysis:

1. The easternmost OCS blocks and aliquots were removed from leasing consideration because of vessel traffic concerns

2. Aliquots were removed that contain active subsea cables, where development constraints may be present.

The modified area of interest comprises 1,359.3 km^2 (versus 1,433.7 km^2 for the original Call area) and has 62 fewer aliquots than the original Call area.

2 Literature Review

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

- The New Jersey Call and 11 responses to the Call
- Presentations delivered at the New Jersey Renewable Energy Task Force meeting held on December 18, 2012
- The modified New Jersey area of analysis that was developed by BOEM as a result of discussions at the NJ Renewable Energy Task Force meeting on December 18, 2012, and provided to NREL for use in the delineation analysis
- Verbal input received from a conference call on May 30, 2013, with staff representing the New Jersey BPU and Rutgers University
- The report: *An Advanced Atmospheric/Ocean Assessment Program Designed to Reduce the Risks Associated with Offshore Wind Energy Development Defined by the NJ Energy Master Plan and the NJ Offshore Wind Energy Economic Development Act*, prepared by Rutgers University for the New Jersey BPU (Glenn and Dunk 2013)
- Available information (including websites and project reports) on current practices for array spacing used in European offshore wind power projects.

2.1 NREL Review of the Call

NREL was granted confidential access to the 11 responses to the 2011 New Jersey Federal Register Call. These nominations provided insight into the commercial sector considerations for offshore development and wind energy leasing area delineation. Each nomination varied considerably as to the type and amount of information that was provided. Generally, the nominations provided information on siting constraints, project specifications, turbine type and size, array density, foundation type, project capacity, development schedule, and interconnect points. NREL researchers determined if any of the provided information should be evaluated in the leasing area identification and delineation methodology. In addition, the researchers considered factors such as meteorological information, wind plant specifications, and potential wake effects between leasing areas (if the data was provided). Note that in the analysis, NREL did not investigate the potential for diminished value to the lease areas that could result from possible conflicts with the U.S. Department of Defense, U.S. Coast Guard, fisheries, or ecological or competing use restrictions.

Figure 3 is a map of the original NJ WEA that shows a density plot of the NJ WEA Outer Continental Shelf leasing blocks displaying the relative interest among the Call nominations for the whole (43) and partial (34) OCS blocks that are contained in the WEA. The colors indicate the number of nominations expressing interest in specific leasing blocks or aliquots in the NJ WEA. As shown in Figure 3, most developers focused their interest on the southern or middle OCS blocks of the NJ WEA, while the northern and western most areas were less favored. It is important to note that the Call responses were based on the undelineated WEA without knowledge of how individual sites might be encumbered by future neighboring facilities. It is possible that developer interest might shift from that shown in Figure 3 under an auction process with multiple leasing areas that are delineated by BOEM prior to the sale.

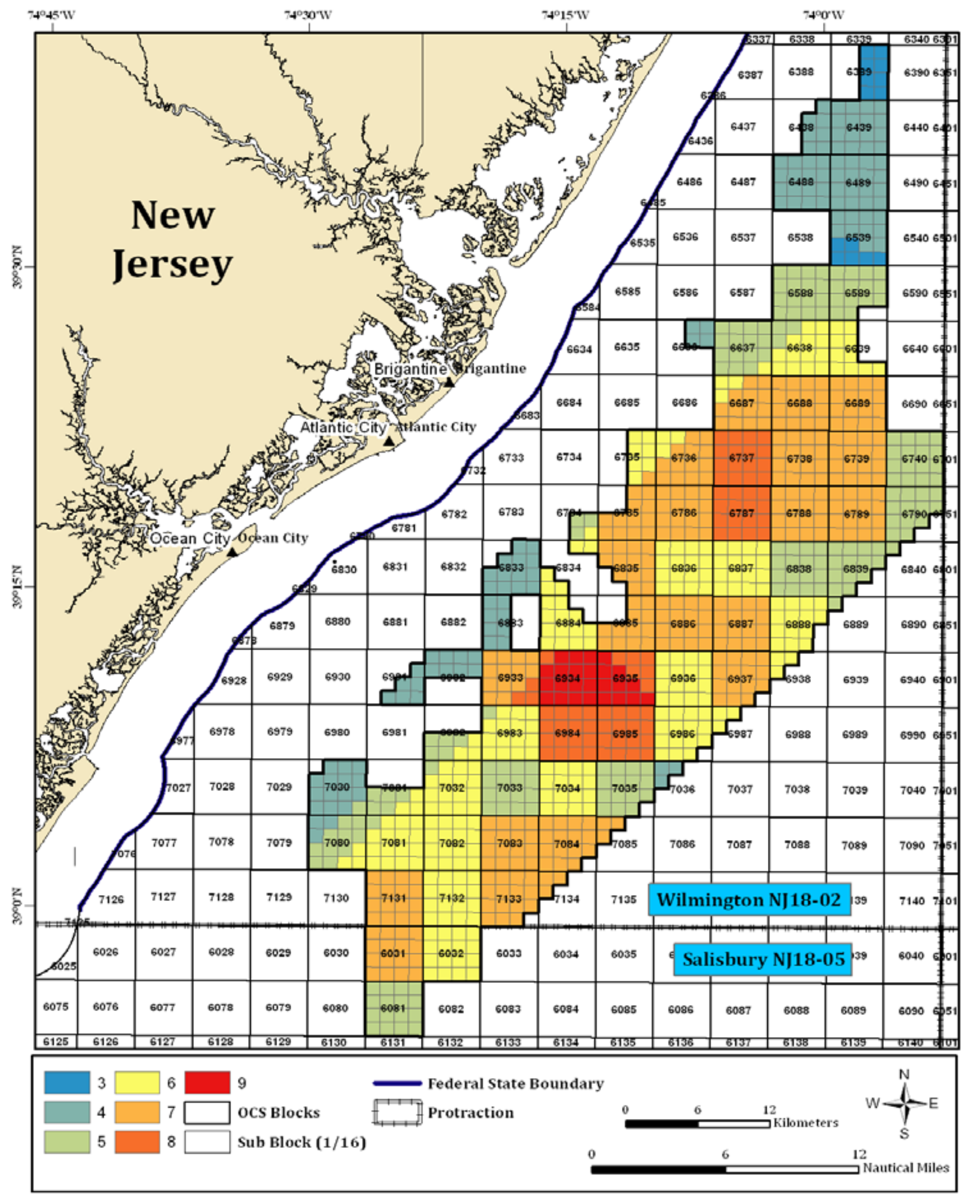


Figure 3. New Jersey Wind Energy Area map showing the number of nominations expressing interest in specific leasing blocks and aliquots from the Call
(Source: BOEM)

A summary of the compiled data extracted by NREL for its review of the nominations is shown in Table 1. Because of confidentiality requirements, the project data from the industry responses were reduced to statistical averages and maximum and minimum values. The latter indicate the wide spread of specifications for the proposed projects. The statistical averages were compared to the nominal values determined from the NREL analysis. The NREL values were based on the area of analysis (which is about 5% smaller area than the original NJ WEA used in the Call) and the four leasing area delineation with the baseline turbine spacing of 10 x 12 rotor diameters (D).

The project nameplate capacity computed by NREL is 3,095 megawatts (MW), which covers the entire area of analysis except for the 8 D buffers between each leasing area established by NREL. However, the project sizes and the spatial extent of the Call nominations varied considerably, ranging from a minimum of 350 MW covering a relatively small area to a maximum of 3,900 MW covering nearly the entire Call area.

Table 1. Summary of Call Statistics from the BOEM New Jersey WEA Responses
(Source: NREL)

	Average	Maximum	Minimum	NREL Values
Project nameplate capacity [megawatts (MW)]	1,568	3,900	350	3,095
Turbine nameplate capacity (MW)	5	8	3	5
Average wind speed in meters per second (m/s) at 90 meters (m)	8.5	9.5	7.5	8.5
Net capacity factor (%)	38.3	42.3	34.4	42.2
Proposed project area (km^2)	593.9	1,280.1	262.2	1,359.3
Array spacing in rotor diameters (D)	10 D x 11 D	15 D x 15 D	7D x 10D	10D x 12D
Array turbine density (MW/km^2)	3.0	4.6	1.4	2.6
Number of turbines	325	650	70	619
Maximum depth (m)	34	43	30	38
Project development time frame (years)	9.75	19	6.5	N/A

Notes:

1. NREL used the NJ area of analysis from December 18, 2012, for its analysis, which differs from the original WEA considered by developers during the Call.
2. NREL's array turbine density computation assumes the NREL reference turbine 5-MW nameplate power capacity and 126-m rotor diameter (Jonkman et al. 2009).
3. NREL's net capacity factor is the gross capacity factor after wake losses only.

The average turbine densities for the Call area ranged from 1.4 to 4.6 MW/km^2 and the mean value was 3.0 MW/km^2 (based on information available from nine out of eleven nominations), which corresponds to a spacing of about 10 D x 11 D. This spacing is comparable to the 10 D x 12 D spacing used by NREL for the baseline case of the New Jersey area of analysis. The spacing in the Call nominations ranged from a minimum of 7 D x 10 D to a maximum of 15 D x 15 D.

Some of the data provided here are inferred from the area of interest provided by each nomination and the proposed total size of the projects. For example, some nominations provided only estimates of total megawatt capacity for specific areas of interest and indicated that details related to turbine spacing, layout, and buffers would be determined at the appropriate project development stage.

The NREL values for all of the selected parameters are within the range of the maximum and minimum values of the nomination responses. NREL's net capacity factor is the gross capacity factor after wake losses only and does not consider other losses, such as availability and electrical losses, which were generally considered in the nomination responses. These other losses, not considered by NREL, can reduce the capacity factor on the order of about 10%. Therefore, NREL's gross capacity factor value of 42.2% may be reduced to a net capacity factor of around 38% if these other losses are considered.

2.2 Array Spacing Assumptions and Comparison to Current Practices

The wind turbine array spacing used by NREL in the analysis was established following discussions and feedback from BOEM, the New Jersey BPU, and Rutgers University. The consensus was that the following three array spacing scenarios would be used in the modeling: 1) 10 D x 12 D, which would be the base case and comparable to the average spacing proposed in the Call responses, as shown above; 2) 10 D x 15 D, which is a wider spacing intended to reduce wake losses; and 3) 8 D x 8 D, which is a closer spacing used by NREL in previous offshore assessments. The 8 D x 8 D spacing and array density of 5.0 MW/km^2 are consistent with the NREL wind resource estimations carried out in 2010 (Schwartz et al 2010) and used by NREL to calculate gross offshore potential in the United States (Musial and Ram 2010).

In an effort to compare the assumptions of array density used in this study to current practices, NREL conducted an assessment of the largest offshore wind power projects that are currently operating or under construction with a capacity of 200 MW or greater. The results of the assessment for the 18 offshore projects and the comparison to the assumptions used in the NJ analysis are shown in Figure 4. Table 2 lists the 18 projects, which range in size from 207 MW to 630 MW, and the average turbine densities, which range from 3.5 to 8.8 MW/km^2. The mean turbine density for all 18 projects is 6.0 MW/km^2. By comparison, the turbine density is 5.0 MW/km^2 for 8 D x 8 D spacing, 2.6 MW/km^2 for 10 D x 12 D spacing, and 2.2 MW/km^2 for 10 D x 15 D spacing, which are the turbine spacing scenarios used in the New Jersey analysis. The turbine density of 5.0 MW/km^2 or 8 D x 8 D spacing used in the analysis more closely represents the average of the 18 offshore projects, whereas the wider spacings of 10 D x 12 D and 10 D x 15 D have lower densities than the current industry projects.

The mean turbine array density of 6.0 MW/km^2 for current offshore wind power projects is twice the mean turbine array density of 3.0 MW/km^2 for the developers' responses to the Call. The range of turbine array density values in the Call responses is 1.4 to 4.6 MW/km^2, which can be compared to a range of 3.5 to 8.8 MW/km^2 for the current offshore wind power projects. This comparison of turbine densities between the Call responses and current industry offshore projects suggests that the general trend in the nascent U.S. offshore wind industry (at least for proposed developments in offshore New Jersey) leans toward wider spacing than the current practices used in large offshore wind projects.

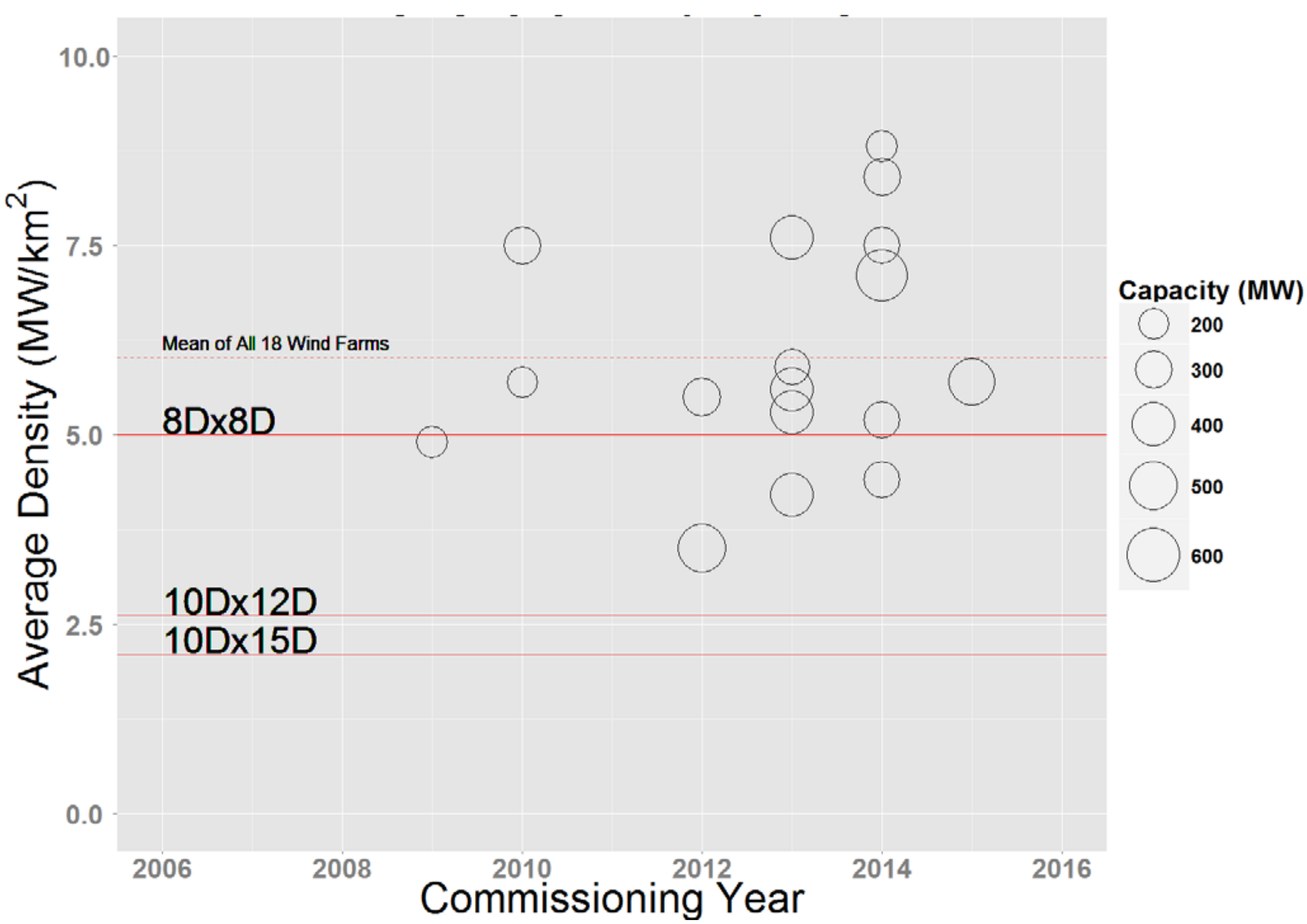


Figure 4. Average turbine array density for 18 large (>200 MW capacity) offshore wind power projects; solid red lines indicate the array density for the spacing scenarios used by NREL in the New Jersey assessment
(Source: NREL)

Note that the industry array density data in Figure 4 do not appear to show any obvious trends that could help predict future array densities. One major factor that may mask any trends could be cable costs. Cable costs are an important factor that constrains turbine spacing. Ultimately the optimum array density must be assessed taking in to account many variables including wake losses, bottom conditions, distance to shore, and competing use issues as well as cable cost. Although wider turbine spacing reduces wake losses and potentially reduces turbine maintenance costs, it increases cable costs and other costs associated with development. This may be the reason that wider spacing is not being adopted as aggressively as the NJ Call responses would indicate. However, a full analysis of the cable costs is beyond the scope of this study.

Table 2. List of 18 of the Largest Offshore Wind Power Projects (>200 MW Capacity)
(Source: NREL)

Country	Name of Wind Farm	Installed Capacity (MW)	Area of Wind Farm (km2)	Average Turbine Density (MW/km2)	Commissioning Date (year)
United Kingdom	London Array 1	630	100	5.5	2013
United Kingdom	Gwynt y Mor	576	79	7.1	2014
United Kingdom	Greater Gabbard	504	147	3.5	2012
United States	Cape Wind	468	62	5.7	2015
Germany	Bard	400	59	5.3	2013
Germany	Borkum West 2	400	56	5.6	2013
Germany	Global Tech 1	400	41	7.6	2013
Denmark	Anholt	399.6	88	4.2	2013
United Kingdom	Sheringham Shoal	316.8	35	5.5	2012
United Kingdom	Thanet	300	35	7.5	2010
Germany	Nordsee Ost	295.2	24	8.4	2014
Germany	Baltic 2	288	30	7.5	2014
Germany	Dantysk	288	66	4.4	2014
Germany	Meerwind Sud und Ost	288	42	5.2	2014
United Kingdom	Lincs	270	35	5.9	2013
Belgium	Northwind	216	14.5	8.8	2014
Denmark	Horns Rev 2	209.3	33	4.9	2009
Denmark	Rodsand 2	207	34	5.7	2010

3 NREL Methodology

3.1 Overview of Methodology

NREL's technical assessment of the delineation of leasing areas included the use of input data to model and compare key parameters such as maximum development capacity, wind speed and direction, capacity factor, 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.

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 New Jersey analysis 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 a 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 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-meter (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 New Jersey area of analysis 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. The MERRA data confirmed the general wind speed and direction characteristics of the WRG/B data. The spatial and temporal resolution of the MERRA data is insufficient to characterize the New Jersey area of analysis but does provide a sound basis for validation. In addition, NREL usually validates modeled offshore data to measured data from available buoys with credible data records in the area of interest. However, the New Jersey area of analysis is not near any offshore buoys that could provide reliable validation points. We compared the WindMap data to measurements from Buoy 44009 of the

National Data Buoy Center (NOAA 2013) and found reasonable agreement with the modeled data. However, the buoy is located 53 km southwest of the southern tip of the New Jersey area of analysis, which is too far from the area of analysis for accurate comparison. Given the lack of measurements available offshore and the coarse resolution of other modeled data sets, the WRG/B data files used for this study provided the best current wind resource information for the New Jersey area of analysis.

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. OpenWind Enterprise is intended for commercial applications and 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 can be related to measurement, the effect of wake meandering, and even fundamentals such as the correct choice of free-stream wind speed profile (Barthelmie et al. 2010). Observations have revealed that turbine wakes sometimes do not travel in a straight line but may shift directions back and forth; otherwise known as wake meandering. 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 leasing areas using the turbine spacing specified by NREL. Square or triangular tiling is used with manually adjusted bearing, obliquity, and offset to obtain the desired number of turbines. In the analysis, a minimum setback of 8 D or approximately 1 km was imposed from the delineation line to the first turbine. NREL did not change this setback parameter when the spacing was increased in subsequent modeling runs. 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 onshore 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.

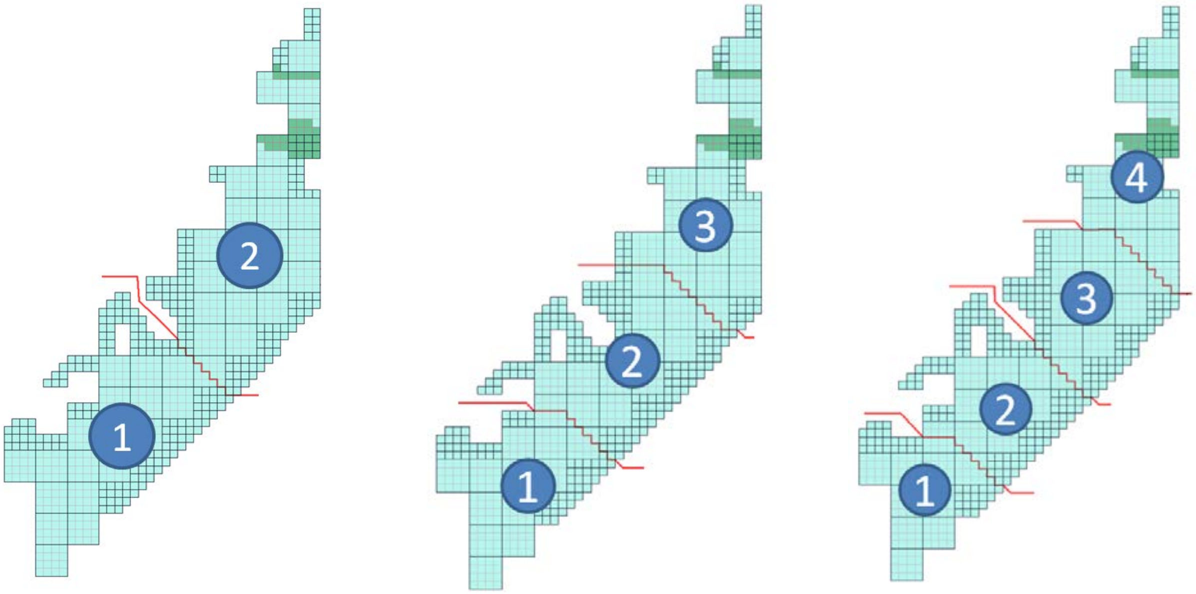
3.4 Overview of Approach to Delineation Assessment

The primary objectives of this analysis were:

- To develop a technical methodology and approach to delineate leasing areas within the modified New Jersey area of analysis, such that the leasing areas—when aggregated—are equal to the total area within the area of analysis. NREL considered several criteria provided in Table 3.
- To evaluate different delineation options and identify the advantages and disadvantages of each option assessed; considering the various physical factors internal and external to the defined leasing areas.

In analyzing the delineation options for the area of analysis and 10 D x 12 D baseline turbine spacing, NREL researchers concluded that a delineation strategy using a 75-degree turbine grid orientation and mostly northwest-southeast diagonal line delineations was optimal in maximizing developable area, minimizing the length of delineation boundaries, balancing bathymetry concerns, and providing essential coastal access. NREL developed and evaluated three different delineation strategies for two, three, and four leasing areas (shown in Figure 5).

In some of the delineation options, balancing these factors resulted in delineation lines that were a combination of straight west-east and diagonal northwest-southeast lines. In Figure 5, the green-shaded cells in the northern part of the area of analysis are aliquots that were removed and contain active subsea cables, where development constraints may be present.



A B C

Figure 5. NJ area of analysis leasing area delineation options developed and evaluated by NREL: (A) two leasing areas, (B) three leasing areas, and (C) four leasing areas. These leasing area options provide insights on the merits of possible delineation strategies.
(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 for the New Jersey Offshore Assessment
(Source: NREL)

Quantitative Evaluation Criteria	Qualitative Evaluation Criteria
Total area (km^2 and acres)	Distance from shore
Maximum installed capacity [megawatts (MW)]	Technology challenges
Bathymetry [meters (m)]	Development cost
Annual average wind resource [meters per second (m/s)]	
Gross capacity factor (%)	
Wake losses (%)	
Array orientation angle (degrees)	
Turbine spacing within array [rotor diameters (D)]	
Capacity factor after wake losses (%)	
Annual energy production [gigawatt-hours (GWh)]	

For the four leasing area delineation, NREL performed additional analyses and comparisons to assess the effects of different wind turbine spacing on wake losses, development potential, and annual energy production.

The results of these analyses are discussed in Section 4.

4 Discussion of Results

4.1 Overview of Delineation Results

The New Jersey area of analysis was found to have about 1,360 km^2 of total area, which is capable of supporting up to four separate leasing areas. NREL researchers conducted analysis to examine scenarios for delineation strategies to divide the area of analysis into two, three, and four leasing areas, respectively.

NREL's approach to delineation focused on the quantitative and qualitative criteria presented in Table 3. While each criterion was considered by NREL, only the criteria in Table 4 were given an independent quantitative analysis. During the analysis, researchers investigated the capacity to support offshore wind projects of various sizes for the different delineation strategies. One of the goals was to understand the importance of wake losses for the different leasing area delineation options. The relative importance of wake effects was examined by analysis of key variables such as maximum capacity, turbine spacing, internal buffers, and grid orientation.

Table 4 provides a comparison of the quantitative results for the three different delineation options assessed by NREL for the New Jersey area of analysis in Figure 5. Each option was assessed for the baseline turbine array spacing of 10 D x 12 D. The effects of some other spacing scenarios are examined later in this section.

Wind turbine array modeling was based on the NREL 5-MW reference turbine (Jonkman et al. 2009) which has a 126 m diameter. The 10 D x 12 D spacing used by NREL for the New Jersey area of analysis baseline case is comparable to the average spacing of about 10 D x 11 D from the developers' responses to the Call (see Table 1). The 10 D x 12 D results in lower wake losses and provides a lower estimate of potential capacity in comparison to the 8 D x 8 D spacing used by NREL to calculate the gross potential in the United States (Musial and Ram 2010) and which reflects the common practices currently used in large offshore wind projects (as shown in Figure 4 and previously discussed in Section 2).

As shown in Table 4, the analysis covered a wide range of variables but focused on the physical site characteristics and how they might affect the development potential of one leasing area relative to the others. In the three and four leasing area delineation options, NREL increased the size of the middle leasing areas compared to the outer areas to compensate for the higher wake losses and reduced energy production from wake effects caused by shadowing from upstream neighboring wind projects. The middle leasing areas are about 25% larger than the southernmost area to provide the developer with the flexibility to add internal buffers to reduce wake effects from the adjacent leasing area. The southern leasing area is the smallest because it has the best exposure to the prevailing winds from the southwest directions. The wake losses range from 9.2% to 9.6% in the middle areas and 6.9% to 8.1% in the outer areas for the three and four leasing area options. In all three options, all leasing areas have a maximum development potential greater than 500 MW, ranging from more than 1,600 MW potential development capacity for each area in the two leasing area option, to more than 600 MW for each area in the four leasing area option.

Table 4. Analysis for Three Different Delineation Options using 10 D x 12 D Baseline Turbine Spacing

(Source: NREL)

	Two Leasing Area Delineation		Three Leasing Area Delineation			Four Leasing Area Delineation			
Parameter	Leasing Area 1	Leasing Area 2	Leasing Area 1	Leasing Area 2	Leasing Area 3	Leasing Area 1	Leasing Area 2	Leasing Area 3	Leasing Area 4
Total area (km^2)	640.8	679.68	383.04	518.4	442.08	276.48	372.96	397.44	298.08
Total area (1000 acres)	158.35	167.95	94.65	128.1	109.24	68.32	92.16	98.21	73.66
Average depth (m)	24	25	25	24	24	25	24	26	24
Bathymetry – depth range (m)	16-38	17-34	16-37	16-34	17-35	15-38	16-34	17-34	17-32
Average wind speed at 90 m (m/s)	8.4	8.6	8.4	8.5	8.6	8.4	8.4	8.5	8.6
10D x 12D - 75 degree Grid									
Gross capacity factor (CF) (%)	45.4	46.5	45.4	45.7	46.8	45.4	45.4	46.1	47
Potential capacity (MW)	1660	1780	945	1185	1075	665	850	890	690
Wake losses (%)	8.9	9.1	8.1	9.5	7.9	7.3	9.2	9.6	6.9
Gross CF after wake losses (%)	41.3	42.3	41.7	41.3	43.1	42.1	41.2	41.7	43.7
Annual Energy Production (GWh)	6016	6597	3455	4293	4062	2451	3072	3252	2644

NREL and BOEM agreed that more in-depth analysis would be performed to assess the effects of different wind turbine spacing on wake losses, development potential, and annual energy production. It was decided to focus on the four leasing area delineation option for this analysis. This configuration offered the highest number of leasing areas and therefore provided the best assessment of wake effects between leasing areas. Also, the four leasing area delineation can represent the two leasing area option fairly closely if the two leasing areas on either end are combined, since the center cut is in the same location. Although these parametric studies on the effects of turbine spacing were not performed for the two and three leasing area delineations, the results from four leasing area delineation were expected to provide sufficient insight on the effects of wind turbine spacing for the other delineations.

As such, we conducted the modeling and compared the results in Table 5 for the following five scenarios of the four leasing area option only (for the 10 D x 12 D spacing only, we presented the results in Table 4 for all leasing area options).

- 10 D x 12 D spacing, (Baseline case)
- 8 D x 8 D spacing, (Represents the spacing used in NREL's estimates of gross wind potential for the United States, and is comparable to the typical spacing used offshore wind projects as shown in Figure 4
- 10 D x 15 D spacing, which represents a wider spacing scenario than that proposed in most of the Call
- Limit of 500 MW at 10 D x 12 D spacing in each leasing area
- Limit of 500 MW at 8 D x 8 D spacing in each leasing area.

Table 5. Analysis for the Four Leasing Area Delineation with Comparison of Different Spacing and Development Options
(Source: NREL)

Parameter	Four Leasing Area Delineation			
	Leasing Area 1	Leasing Area 2	Leasing Area 3	Leasing Area 4
Total area (km^2)	276.48	372.96	397.44	296.64
Total area (1000 acres)	68.32	92.16	98.21	73.3
Average depth (m)	25	24	26	24
Bathymetry – depth range (m)	15-38	16-34	17-34	17-32
Average wind speed at 90 m (m/s)	8.4	8.4	8.5	8.6
8D x 8D - 0 degree Grid				
Wake losses (%)	11.2	13.4	13.9	10.8
Gross capacity factor (CF) (%)	45.4	45.4	46.1	47.0
Gross CF after wake losses (%)	40.3	39.3	39.7	41.9
Potential capacity (MW)	1,320	1,630	1,760	1,405
Annual Energy Production (GWh)	4,660	5,618	6,128	5,162
10D x 12D - 75 degree Grid				
Wake losses (%)	7.3	9.2	9.6	6.9
Gross capacity factor (CF) (%)	45.4	45.4	46.1	46.9
Gross CF after wake losses (%)	42.1	41.2	41.7	43.7
Potential capacity (MW)	665	850	890	690
Annual Energy Production (GWh)	2451	3072	3252	2644
10D x 15D – 75 degree Grid				
Wake losses (%)	6.3	8.1	8.5	6
Gross capacity factor (CF) (%)	45.5	45.4	46.1	47.0
Gross CF after wake losses (%)	42.6	41.7	42.2	44.2
Potential capacity (MW)	525	685	720	555
Annual Energy Production (GWh)	1958	2507	2665	2148
8D x 8D – Limit 500 MW - 0 degree Grid				
Wake losses (%)	7.6	8.2	7.5	5.8
Gross capacity factor (CF) (%)	45.2	45.3	45.8	46.8
Gross CF after wake losses (%)	41.8	41.6	42.4	44.1
Potential capacity (MW)	500	500	500	500
Annual Energy Production (GWh)	1833	1823	1857	1934
10D x 12D – Limit 500 MW - 75 degree Grid				
Wake losses (%)	6.1	7.2	7.2	5.7
Gross capacity factor (CF) (%)	45.4	45.4	46.1	47.0
Gross CF after wake losses (%)	42.6	42.1	42.8	44.3
Potential capacity (MW)	500	500	500	500
Annual Energy Production (GWh)	1867	1844	1875	1940

4.2 Delineation Strategy

During the study, three different candidate delineations were developed and analyzed with different turbine spacings. The objective was to create three options for two, three, and four leasing areas, respectively, and to provide enough data to allow BOEM to choose the best option for economic development of the entire New Jersey area of analysis. Several physical parameters were fixed in defining the delineation boundaries including wind resource, BOEM leasing grid, the boundaries set by BOEM for the area of analysis, and the corresponding bathymetry. As shown in Figure 2, the New Jersey area of analysis has a rhomboid-(parallelogram) shaped geometry with its long sides oriented approximately parallel to the coast and approximately three times the length of the shorter sides. The NREL delineation methodology for all options used delineations that sectioned the area of analysis along mostly northwest-southeast diagonal lines, as shown in Figure 5. A diagonal delineation line provided each leasing area, regardless of the number of areas considered, a frontage along the western border closest to the shoreline, which is necessary for construction access, service, and cable routing. Northwest-southeast diagonal delineations also divided the areas of deeper water located in the easternmost aliquots more or less evenly among the leasing areas.

Balancing wake effects equitably was the most difficult factor to resolve in balancing the development potential of the New Jersey leasing areas. The orientation of the New Jersey area of analysis creates a disadvantage for some of the leasing areas as the long sides of the area are also parallel to the dominant prevailing winds from the southwest. This orientation results in the unavoidable creation of leasing areas that have neighboring wind plants on their windward side for much of the year, and some areas with adjacent wind plants on two sides. To compensate for this disadvantage, the delineation lines were drawn to allocate additional aliquots to the middle leasing areas that will be more handicapped by wake losses. This variation in assigned leasing area can be seen in the total area provided in Table 4, given in both acres and square kilometers.

In addition, researchers assumed that even in the case of full build-out, developers will self-enforce an 8 D buffer or setback along the delineation lines to maintain desired minimum turbine layout spacing from neighboring projects. Some opportunities for external buffers resulted from the irregular convoluted shape of the boundary on the west side and helped guide the location of delineation lines. For some options, the delineations lines were drawn to enhance these irregular boundaries for turbine wake dissipation. Examples of where this strategy was used can be seen in Figure 6 where significant protuberances could provide sections of more unobstructed winds.

Generally, the diagonal delineation lines shown in Figure 5 were designed to maximize developable area, balance bathymetry concerns, and provide essential coastal access.

4.3 Maximum Development Capacity

NREL researchers evaluated the maximum development capacity of the leasing areas for each delineation option by creating turbine layouts that maximized the number of turbines in each leasing area with specified turbine spacing. Example layout maps with the setback buffer along the delineation lines are shown in Figure 6 for the four leasing area delineation option.

Figure 6. New Jersey area of analysis and layout maps of the four leasing area delineation for the 8 D x 8 D spacing with a zero-degree orientation (left) and 10 D x 12 D spacing with a 75-degree orientation (right)
(Source: NREL)

Circular symbols scaled to 8 D are used in the layout for the 8 D x 8 D spacing (see the left map in Figure 6). The grid orientation angle shown is zero degrees corresponding to the lowest wake losses for the 8 D x 8 D grid, and the array is aligned with the leasing area grids.

Elliptical symbols scaled to 10 and 12 D are used in the layout for the 10 D x 12 D spacing (see the right map in Figure 6). The grid orientation angle shown is 75 degrees corresponding to the lowest wake losses for the 10 D x 12 D grid. NREL also estimated the potential installed capacity for a 10 D x 15 D turbine spacing scenario that is not shown in the figure.

NREL found that as turbine spacing increases, the development potential for each leasing area decreases (as shown in Figure 7) for the four leasing area option shown in Figure 5c. These data are also provided in Table 5. Estimates of the potential capacity for the 8 D x 8 D spacing in each of the four leasing areas are almost twice those for the 10 D x 12 D spacing. The potential capacity ranges from 1,320 MW to 1,760 MW for the 8 D x 8 D spacing and from 665 MW to 890 MW for the 10 D x 12 D spacing. For the 10 D x 15 D spacing, the potential capacity ranges from 525 MW to 720 MW and is approximately 20% less than the 10 D x 12 D spacing.

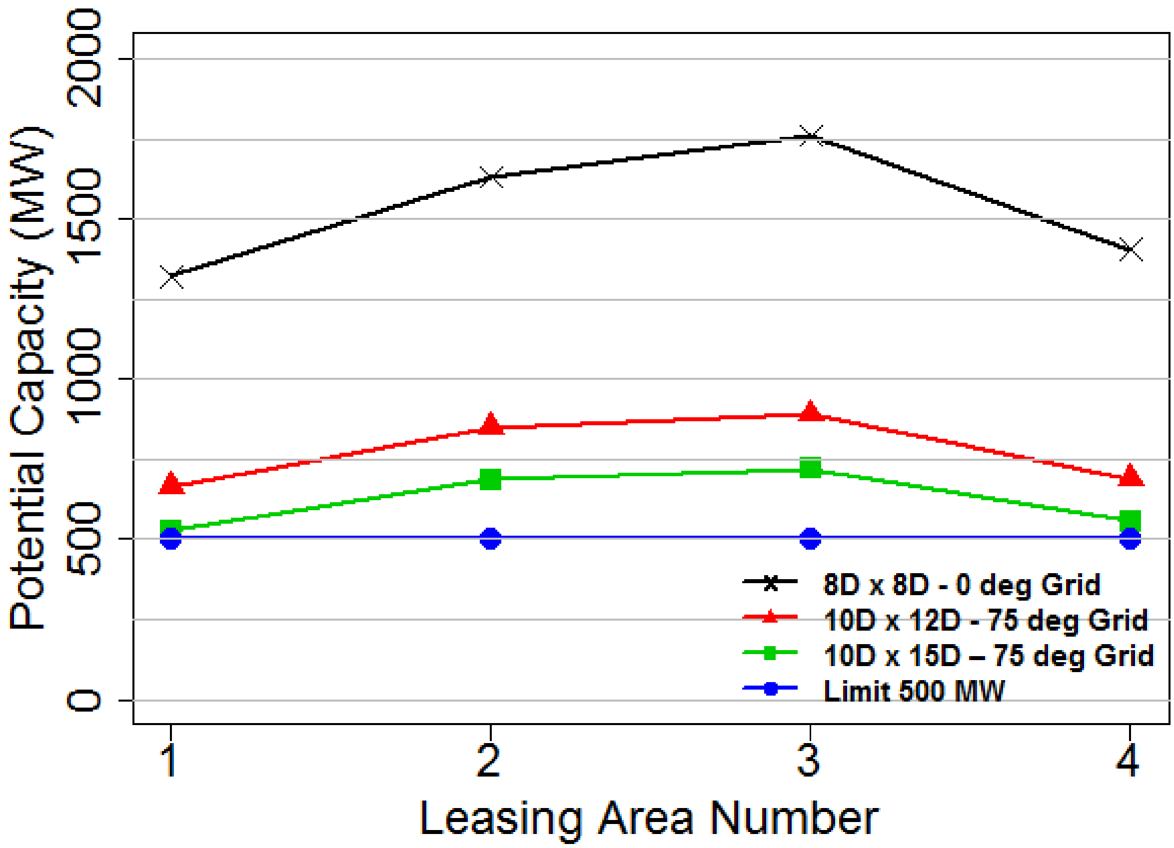


Figure 7. Maximum development potential for the four leasing area delineation strategy of the New Jersey area of analysis with three different turbine spacing options and the 500 MW limit
(Source: NREL)

4.4 Bathymetry Considerations

The water depth, or bathymetry, was considered when assessing the wind development potential of the leasing areas in the NJ area of analysis. Figure 8 shows a bathymetry map of the area.

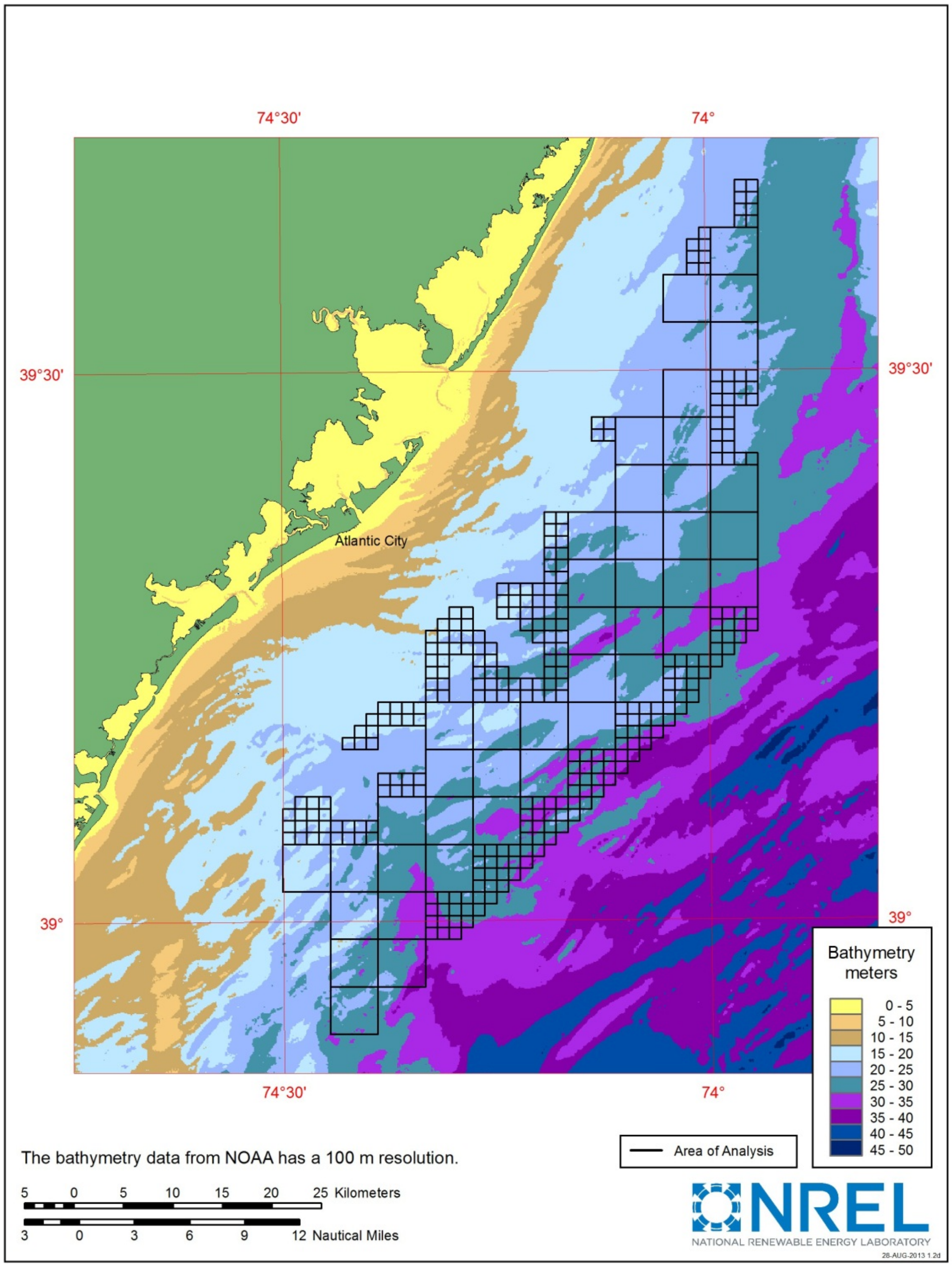


Figure 8. Water depth map for the New Jersey area of analysis
(Source: NREL)

The bathymetry map shows that shallow waters less than 30 m deep are prevalent over most of the region (areas shaded in blue colors). Deeper water of 30 m and greater (purple colors) is located near the eastern edges of the region, with some patches near the geographic center.

Table 6 provides a breakdown of the maximum installed capacity by water depth using 10 D x 12 D spacing for the three delineation options shown in Figure 5.

Table 6. Maximum Installed Wind Capacity by Leasing Area and Water Depth for the New Jersey Area of Analysis for Three Leasing Area Delineation Options using 10 D x 12 D Spacing
(Source: NREL)

	Two Leasing area Delineation (MW)		Three Leasing area Delineation (MW)			Four Leasing area Delineation (MW)			
DEPTH m	Zone 1	Zone 2	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	Zone 4
0-15m	0	0	0	0	0	0	0	0	0
15-20m	325	145	130	265	90	135	220	75	60
20-25m	625	940	310	450	675	195	300	340	495
25-30m	550	580	415	355	260	250	240	410	130
30-35m	155	115	85	115	50	70	90	65	5
35-40m	5	0	5	0	0	15	0	0	0
TOTAL (MW)	1660	1780	945	1185	1075	665	850	890	690

Table 6 shows that the percentage of deep water above 30 m (highlighted in blue) represents less than 10% of the total capacity in most of the leasing areas. Therefore, most of the areas would not be affected significantly by the water depth in terms of cost and development challenges imposed by water depth.

Depth considerations are important with respect to project risk and cost. Figure 9 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. The figure shows that the majority of the projects are installed in waters less than 30 m 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 Baltic and North Seas, and European offshore wind developers are only beginning to venture into deeper waters.

The analysis indicated that all leasing areas considered in the New Jersey area of analysis have ample shallow water, with mean depths of about 24 m to 26 m (see Table 4) to support large projects of at least 500 MW for the 10 D x 12 D spacing (see Table 6) using proven shallow water technology. The minimum depths of the proposed leasing areas range from 15 m to 17 m, and the maximum depths range from 32 m to 38 m.

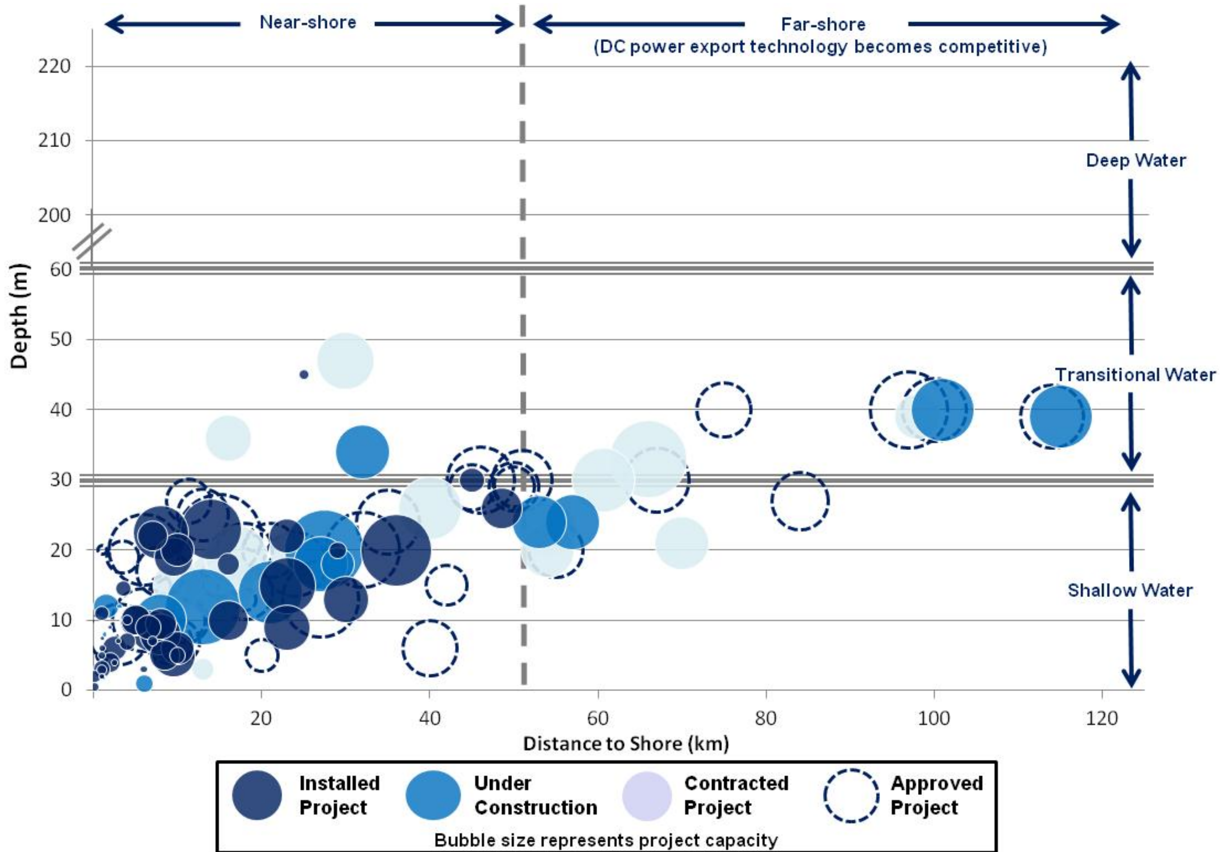


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Figure 9. Current offshore wind projects in Europe: installed, under construction, contracted, and approved as a function of water depth and distance to shore
(Source: NREL)

4.5 Wind Resource

The New Jersey wind climate is marked by nor'easters from November to April (Dvorak et al. 2012), which can lead to strong winds and extreme conditions. Tropical cyclones are rare but are possible—up to Category 3 on the Saffir-Simpson scale—and must be taken into account in the structural design. During the summer months, winds are generally lower and sea breezes play a larger role; especially off the coast of New Jersey. Sea breezes can be quite strong and typically peak in the afternoon (Glenn and Dunk 2013). Although storm activity exists in this region, no significant long-term trends existed during the 20th century (Zhang et al. 2000).

The annual average wind speed determined from the AWS Truepower WRG/B data described in Section 3.2 is shown in the map in Figure 10 for the New Jersey area of analysis. The figure shows that the wind speed varies from approximately 8.3 m/s to 8.7 m/s at 90 m, with highest wind speeds in the northeast and lowest speeds along the most western fringes especially in the south. This wind speed gradient of about 0.4 m/s across the area of analysis can be significant in terms of energy production and capacity factor, but is on the same scale as the typical uncertainty of about +/-0.35 m/s, which 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 also shown in Figure 10, come largely from the southwest (SW) and south-southwest (SSW) directions, but there is a small secondary component from the west-northwest direction. Having a high percentage of the winds from a single prevailing direction sector (SW-SSW) simplifies the siting and layout optimization as opposed to an orthogonal, bimodal wind direction distribution which increases wake losses and complexity of layout optimization. As discussed later in section 4.7.3 for the 500 MW project, array layouts that are roughly perpendicular to the prevailing SW-SSW winds and with large buffers between arrays in the prevailing directions were used by NREL to minimize the wake losses in the 500 MW arrays.

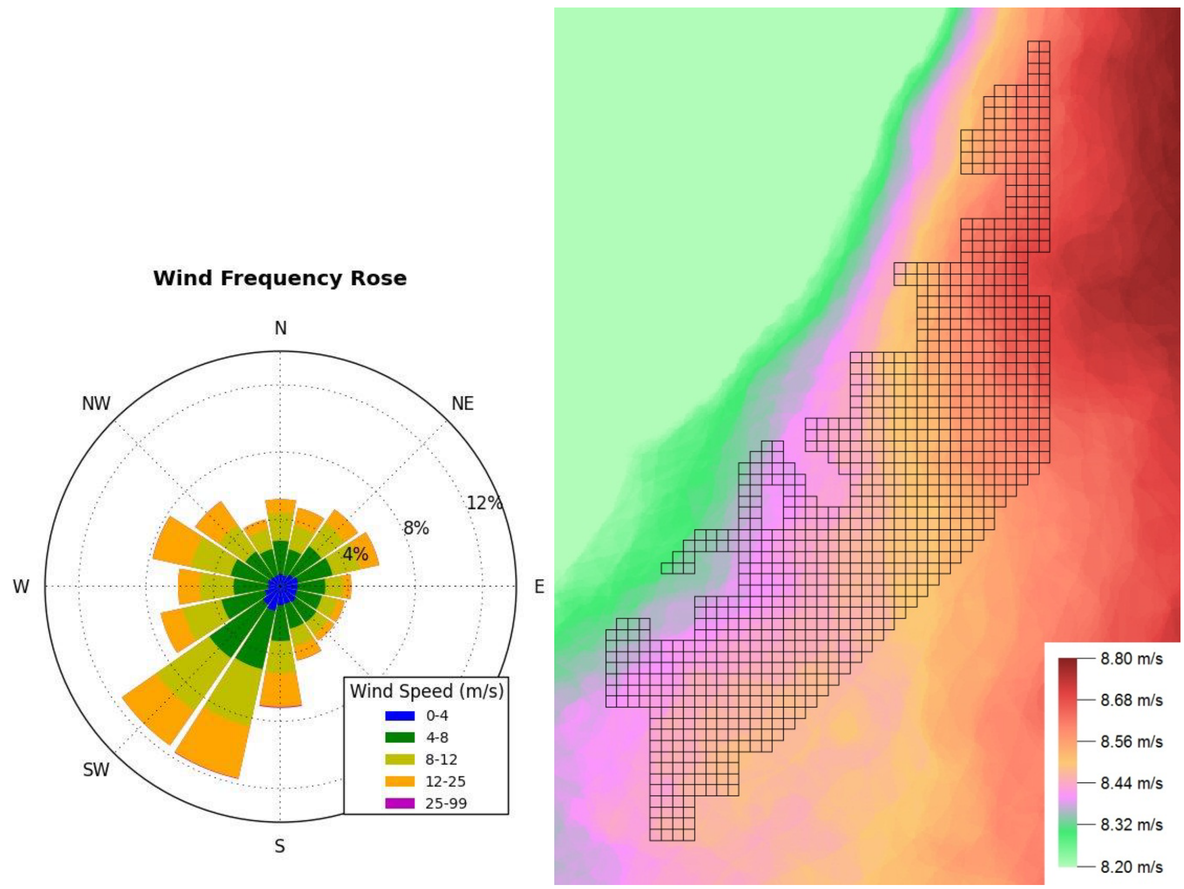

Figure 10. New Jersey area of analysis showing an annual average wind speed in 0.12 m/s increments (right) and a wind frequency rose with prevailing winds from the southwest direction (left)
(Source: NREL)

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 tool, 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 in the range of 45% in the southern leasing areas, and up to 47% in the northern areas based on the NREL 5-MW reference turbine. This low variability in gross capacity factor indicates a fairly uniform resource distribution across the New Jersey area of analysis and low sensitivity to the chosen delineation strategy. The capacity factor was also computed after accounting for wake losses. For the four leasing area delineation option (see Table 5), the capacity factors were estimated to range from 39% to 42% for the 8 D x 8 D spacing and from 41% to 44% for the 10 D x 12 D spacing. The lowest values typically occurred in the middle leasing areas where wake losses are the greatest and the highest values typically occurred in the northern leasing area where wind resources are the greatest. 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 energy production losses and increased 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 facility layout. Further wake losses can also be induced by the presence of neighboring wind facilities.

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 11 is a photo of the Horns Rev offshore wind facility off the west coast of Denmark. The photo was taken on a day when fog was formed because of 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. Figure 11 shows 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 gridded array with 7 D x 7 D turbine spacing with a turbine array density of 6.4 MW/km^2. See Section 2.2 for more information about typical industry turbine spacing practices.

Figure 11. Horns Rev I wind farm
(Source: Vattenfall, *Photo by Christian Steiness*)

4.7.2 Effect of 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 12.

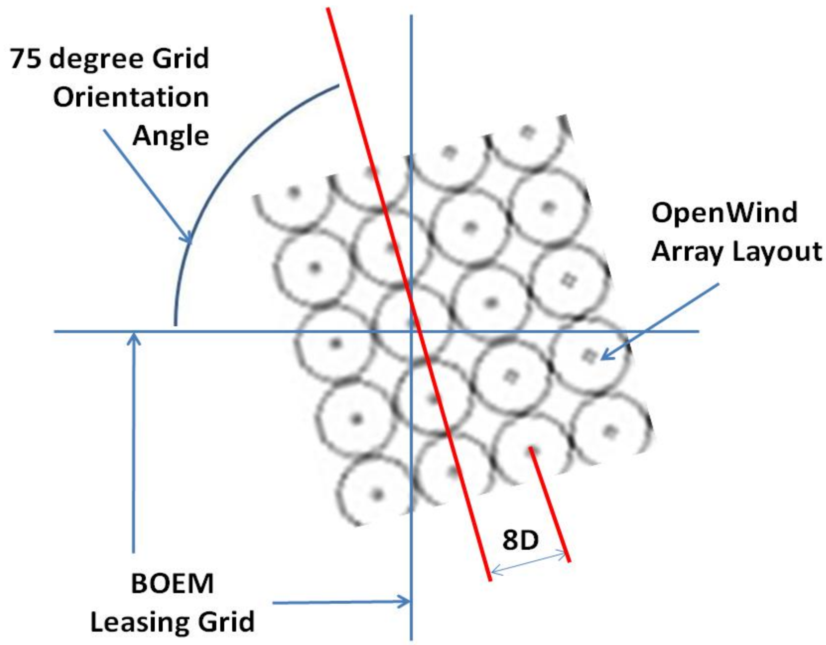

Figure 12. OpenWind uses the BOEM leasing grid as a reference frame for the grid orientation angle of the turbine array, shown for 8 D x 8 D spacing
(Source: NREL)

NREL performed analysis in OpenWind using the wind rose shown in Figure 10 to find the angle relative to the leasing grid with the lowest wake losses. The grid orientation angle was varied by 15-degree increments over the possible range. 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 8 D x 8 D grid array spacing, the grid orientation angle was relatively unimportant in determining the total plant losses. Nevertheless, NREL researchers ran the analysis with the grid orientation angle that delivered minimum losses that varied slightly depending on the symmetry of grid spacing.

The grid orientation angle that yielded the lowest wake losses was found to be at zero degrees for 8 D x 8 D spacing in the New Jersey assessment. This orientation is logical because the prevailing winds (major southwest and minor 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 zero-degree grid orientation (shown in the left map of Figure 6) also allows for the largest number of turbines to be sited within the area of analysis.

The analysis showed that nonsymmetrical arrays had a different grid orientation angle for minimum losses. For the 10 D x 12 D spacing, the analysis revealed that a grid orientation angle of 75 degrees (shown in the right map of Figure 6) yields the lowest wake losses.

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 the grid orientation. Figure 13 shows the impact of turbine spacing and buffers on wake losses for the four leasing area delineation. The plots show the individual turbines in the layouts with color coding to indicate their efficiency while operating in the array. Each turbine is represented by a single dot. The colors indicate the magnitude in which the turbine is underperforming in the array compared to how it would perform in an unobstructed free-stream wind. Note how the strong degradation in the wind project interior dominates the chart for all turbine spacing and grid orientation scenarios, with the largest degradation occurring for the 8 D x 8 D spacing.

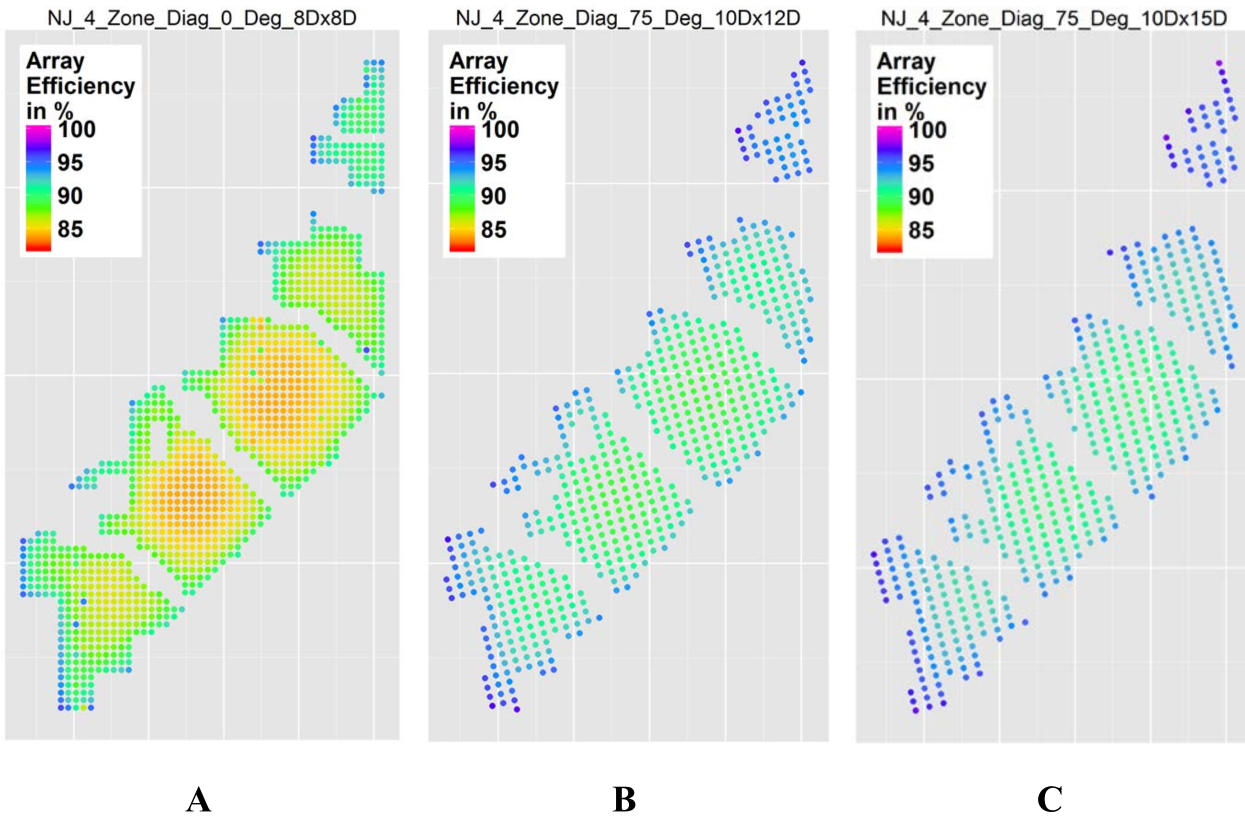

Figure 13. New Jersey area of analysis with the four leasing area delineation showing the effect of turbine spacing and buffers on wake losses. Deep array losses dominate for all grid orientations and all turbine spacings: (A) 8 D x 8 D spacing with a zero-degree orientation, (B) 10 D x 12 D spacing with a 75-degree orientation, (C) 10 D x 15 D spacing with a 75-degree orientation. Wake losses are largest in the middle leasing areas and least in the north and south leasing areas. (Source: NREL)

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 2012; Hansen et al. 2012) based on available wake measurement data. The OpenWind-derived wake loss estimates for the New Jersey area of analysis with the four leasing area delineation and 8 D x 8 D spacing are between 10.8% and 13.9% of total energy (see Table 5) and are within the range of available field data.

Wake losses are significantly lower for the 10 D x 12 D spacing and average from 6.9% to 9.6%. However, the 10 D x 12 D spacing (2.6 MW/km^2) is a larger spacing than that used in any of the large existing offshore projects (see Figure 4). For the 10 D x 15 D spacing (2.2 MW/km^2), average wake losses range from 6.0% to 8.5% and are slightly less than losses for the 10 D x 12 D spacing.

As shown in Figure 10, the prevailing winds in the New Jersey area of analysis are primarily from the southwest with a small component from the northwest. The southwest winds are expected to generate more stable atmospheric conditions whereas the northwest winds are expected to generate more unstable atmospheric conditions. Unstable conditions create more turbulent mixing and accelerated wake decay. Therefore, the middle leasing areas are expected to experience higher wake losses if the upwind leasing area to the southwest is fully developed. For the 8 D x 8 D spacing, the wake losses in the middle leasing areas are 13.4%–13.9%, as compared to 10.8%–11.2% in the end leasing areas (shown in Table 5). For the 10 D x 12 D spacing, the wake losses in the middle leasing areas are 9.2%–9.6%, as compared to 6.9%–7.3% in the end leasing areas. In the 10 D x 15 D spacing, the wake losses are 8.1%–8.5% in the middle leasing areas as compared to 6.0%–6.3% in the end leasing areas. Therefore, highest wake losses in all spacing scenarios occur in the middle leasing areas but decrease with increased spacing, which is apparent in Figure 13.

Figure 14 shows the impact of turbine spacing and buffers on wake losses for a 500-MW project in each of the four leasing areas. Note that the 500-MW project in the northern leasing area (leasing area four) appears in three sections because two buffers containing active subsea cables divide the developable area for this analysis. In Figure 14, the 8 D x 8 D spacing is shown on the left side and the 10 D x 12 D spacing on the right side. NREL designed the layout configurations to minimize wake losses by placing relatively large buffers between the arrays, where feasible, and aligning the 500-MW arrays roughly in a northwest-southeast direction that is perpendicular to the prevailing winds from the southwest. The increased buffers and alignments reduce the deep array effects and resultant wake losses by decreasing the number of turbines within the deep array and increasing the space between arrays. Because the 8 D x 8 D spacing uses only about half the area of the 10 D x 12 D spacing, there is more flexibility in the siting of individual turbines in the 8 D x 8 D 500-MW projects to optimize the alignment and increase the buffers in an effort to reduce wake losses. Furthermore, 10 D x 15 D spacing for a 500-MW project takes up most of the available space within each leasing area; consequently, there is less opportunity to adjust the turbine siting and alignment to further reduce wake effects.

Average wake losses for the New Jersey area of analysis for the 500-MW 8 D x 8 D spacing are estimated to be 7.3%, as compared to an average of 6.6% for the 10 D x 12 D spacing. Wake losses range from 5.8% to 8.2% for the 8 D x 8 D spacing and from 5.7% to 7.2% for the 10 D x 12 D spacing, as shown in Table 5 for the four leasing area delineation. For a 500-MW project, the annual energy production (see Table 5) for the 8 D x 8 D spacing is about 1% to 2% less than that for the 10 D x 12 D spacing. However, the development area required for a 500-MW project with 8 D x 8 D spacing is about half that required for a 500-MW project with 10 D x 12 D spacing. The additional cost of development over the much larger area for 10 D x 12 D spacing should be weighed carefully against the benefits of reduced wake losses.

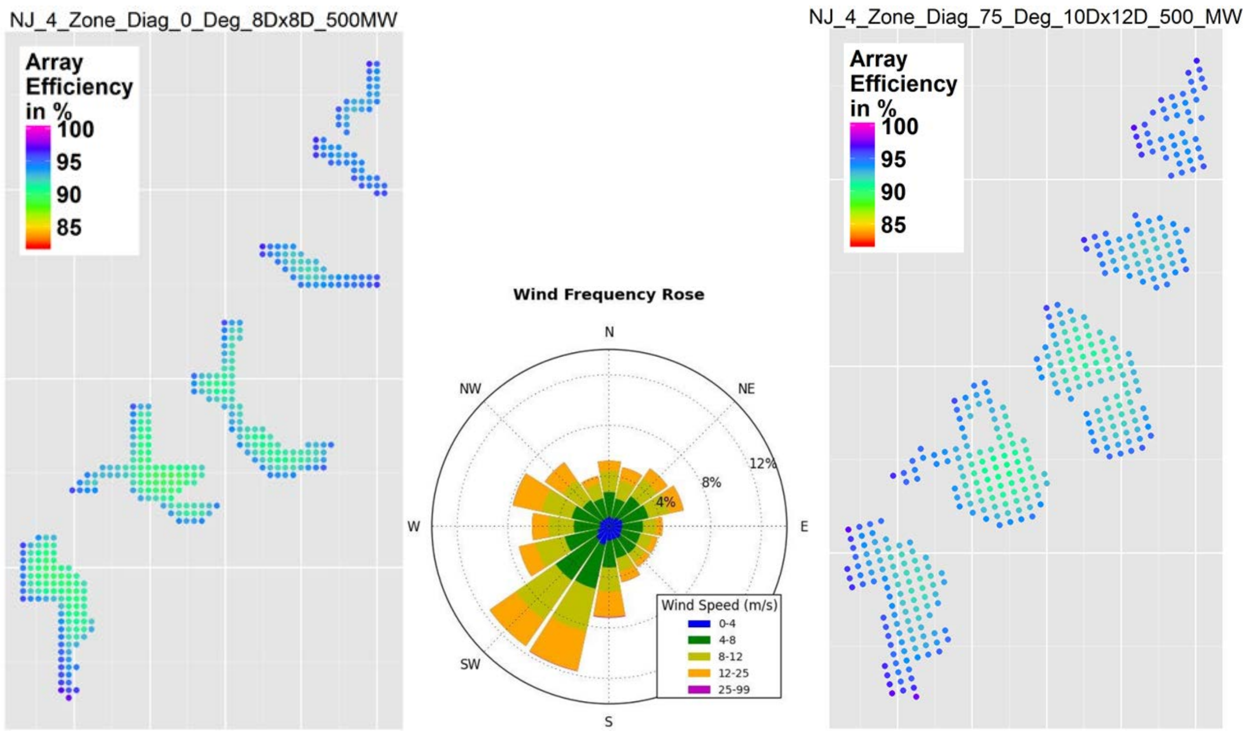

Figure 14. New Jersey WEA with the four leasing area delineation showing the effect of turbine spacing and buffers on wake losses for a 500-MW wind project in each leasing area with 8 D x 8 D turbine spacing (left) and 10 D x 12 D spacing (right)
(Source: NREL)

4.7.4 Inter-Array Wake Losses

Under the development scenarios examined, a portion of the wake losses come from neighboring wind projects in addition to the internally generated wake losses. These external, inter-array losses occur when one wind project disturbs the wind flowing to another project located downstream. For the New Jersey area of analysis, the southern leasing area has the most favorable position because it has the best exposure to the unobstructed prevailing southwest winds. The leasing areas located farther north are impacted by wakes from the more southern projects. A weaker northwest prevailing component may offset this advantage to some degree for the more northerly leasing areas. The middle leasing areas are burdened the most by wake interactions.

Further analysis was conducted to quantify the portion of wake losses coming from external sources (i.e., other wind projects) and the portion that are generated internally by the projects themselves. This analysis examines the 500-MW project shown in Figure 14 for the 8 D x 8 D spacing and 10 D x 12 D spacing. The wake losses for both of these scenarios were examined with full development of 500 MW in all leasing areas, as shown in Figure 14, and with each leasing area operating its 500-MW project individually without the presence of wind turbines in the adjacent leasing areas. These results are presented in Table 7 and in Figure 15. The difference in wake losses between the full 500 MW developments in all leasing areas and the individual unobstructed projects defines the portion of the wake losses that are externally induced by the presence of other wind projects outside the leasing area.

In the southern area (leasing area 1), wake losses with one 500-MW project installed in all four leasing areas are 6%–9% higher than for a single 500-MW plant for both spacing scenarios. Leasing area 1 has the smallest difference in wake losses, which is expected because of the prevailing winds from the southwest directions. The differences are higher for the 10 D x 12 D spacing than the 8 D x 8 D spacing, probably because of the larger area used and smaller buffer for the 10 D x 12 D spacing.

In the middle areas, wake losses with one 500-MW project installed in all four leasing areas are 26%–31% higher than for a single 500-MW wind plant for 10 D x 12 D spacing and 20%–23% higher for 8 D x 8 D spacing. This analysis indicates that inter-array effects on wake losses are significant even with the buffers between the separate projects. We expect the reason for the larger inter-array wake losses with the 10 D x 12 D spacing than the 8 D x 8 D spacing is because the buffers between the four 500-MW projects are smaller for the 10 D x 12 D spacing than for the 8 D x 8 D spacing, since the larger spacing uses a greater portion of the allocated area.

Table 7. Comparison of Individual (Single 500-MW Project) Versus Full Development (Four 500-MW Projects) with 8 D x 8 D and 10 D x 12 D Spacing

(Source: NREL)

	Siting Scenario	8D x 8D Spacing 500 MW Maximum				10D x 12D Spacing 500 MW Maximum			
Parameter		Leasing Area 1	Leasing Area 2	Leasing Area 3	Leasing Area 4	Leasing Area 1	Leasing Area 2	Leasing Area 3	Leasing Area 4
Potential installed capacity (MW)	Individual	500	500	500	500	500	500	500	500
	Full Development	500	500	500	500	500	500	500	500
Wake losses (%)	Individual	7.2	6.8	6.1	5.3	5.6	5.7	5.5	4.8
	Full Development	7.6	8.2	7.5	5.8	6.1	7.2	7.2	5.7
Capacity factor after wake losses (%)	Individual	42	42.2	43	44.4	42.8	42.8	43.5	44.7
	Full Development	41.8	41.6	42.4	44.1	42.6	42.1	42.8	44.3
Annual energy production (GWh)	Individual	1841	1849	1886	1945	1877	1876	1908	1957
	Full Development	1833	1823	1857	1934	1867	1844	1875	1940

In the northern area, wake losses from the development of a 500-MW plant in each of the four leasing areas are 19% higher than those from single wind plant development for 10 D x 12 D spacing and 9% higher for 8 D x 8 D spacing. The northern area also has additional external buffers where wind turbine placement may be constrained because of active subsea cables. The larger buffers and smaller area of the 8 D x 8 D spacing reduce the inter-array wake effects on the 8 D x 8 D 500-MW project in the northern area. Conversely, the smaller buffers and larger area of the 10 D x 12 D 500-MW project significantly increase the inter-array wake effects (as compared to the 8 D x 8 D project).

Considering the entire area of analysis, inter-array effects increase wake losses by about 21% for the 10 D x 12 D spacing and about 14% for the 8 D x 8 D spacing. As previously noted, the inter-array effects on wake losses are greater for the 10 D x 12 D spacing than the 8 D x 8 D spacing because of smaller buffers between the projects and the larger area of the 10 D x 12 D projects, which will encounter the wakes of a neighboring project from a broader range of wind directions.

In summary, when the project size is limited to 500 MW and uses common layouts designed to reduce wake effects, the overall wake losses from 500-MW developments in all leasing areas are reduced (in comparison to losses from developing the maximum capacity) by 20% for the 10 D x 12 D spacing scenario and by 40% for the 8 D x 8 D spacing scenario. In the 500-MW project with adequate buffers and typical layouts, inter-array wake effects are relatively small in comparison to maximum capacity developments with minimal buffers. Therefore, internal wind plant wake losses accounted for the majority of the total wake losses in the 500-MW projects, ranging from 76% to 92% of total wake losses for the 10 D x 12 D spacing and from 81% to 95% of total wake losses for the 8 D x 8 D spacing.

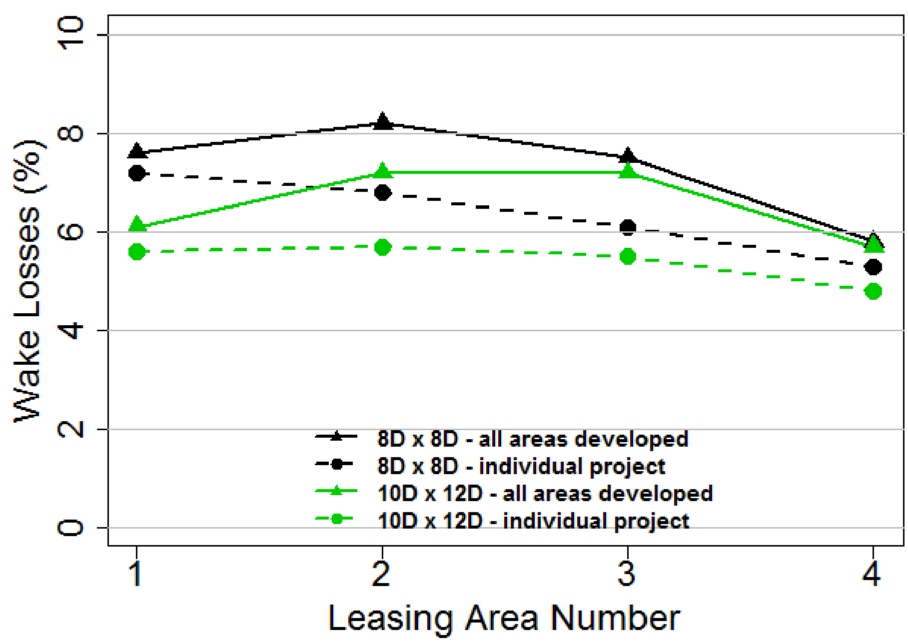

Figure 15. Comparison of wake losses for individual versus full development of 500-MW projects with 8 D x 8 D and 10 D x 12 D spacing. The wake losses in the fully developed area of analysis are contrasted to the wake losses with each leasing area developed individually.
(Source: NREL)

4.7.5 Effect of Turbulence Intensity on Wake Losses

Studies have shown that the turbulence intensity of the wind flow can have a significant effect on the wake losses in offshore wind power plants (Barthelmie et al. 2012; Hansen et al. 2012; Jensen 2007). Measurements of power production and wakes in European offshore wind power plants have verified that wake losses are typically greatest for low turbulence intensity and least for high turbulence intensity wind flow conditions.

For the model simulations of wake losses in OpenWind, the average turbulence intensity value is specified by the analyst. In the Baltic Sea offshore areas where high-quality tall-tower measurement data have been analyzed, the annual average turbulence intensity at turbine heights is typically less than 6% (which is considered to be a low turbulence intensity) and decreases with height (Hansen et al. 2012). Furthermore, the Hansen study shows that turbulence intensities are lowest at wind speeds between 8 and 12 m/s. This implies that for wind speeds in the frequently occurring range of 8–12 m/s, low turbulence intensity can potentially delay dissipation of turbines wakes and further increase wake losses.

Unfortunately, no high-quality wind measurements on turbulence intensities were available for the New Jersey area of analysis.

For this study, NREL researchers conducted a preliminary analysis of the sensitivity of the OpenWind model simulations of wake losses for a large array of 8 D x 8 D spacing to different turbulence intensity values of 5%, 10%, and 15%. This analysis did not show any significant differences caused by turbulence intensity. However, the large array and resultant deep array effects on the wake losses may have overwhelmed any effects caused by turbulence intensity in the simulations. Further simulations using smaller arrays and more open spacing should be evaluated using different turbulence intensities to examine if the results are similar or not to the preliminary findings. In the absence of data for this region and generally low model sensitivity to turbulence intensity, NREL assumed an average turbulence intensity of 10% for the model simulations of the wake losses and energy production.

4.8 Capacity Factor and Potential Annual Energy Production After Wake Losses

As shown in Table 5 for the four leasing area delineation, gross capacity factor was computed after including the performance losses caused by wakes. The wake loss calculations were made for all leasing areas and each array spacing scenario with the leasing areas fully developed and for the 500-MW project case. After wake losses, the capacity factors for the middle leasing areas are reduced to the range of about 39%–40% for the 8 D x 8 D spacing, 41%–42% for the 10 D x 12 D spacing, about 42% for the 10 D x 15 D spacing and for the 500-MW project with 8 D x 8 D spacing, and about 42.5% for the 500-MW project with 10 D x 12 D spacing. It is interesting to note that the capacity factors and wake losses in the middle areas are about the same for the 500-MW 8 D x 8 D projects and fully developed 10 D x 15 D projects. The fully developed 10 D x 15 D projects occupy most of the leasing areas, whereas the 500-MW projects are much smaller in size and have large buffers that reduce the inter-array wake effects. Similarly, we found the annual energy production to be only 1% greater for the 10 D x 12 D projects, but the development area was almost twice as large as that for the 8 D x 8 D projects. It appears that the larger buffers between the 8 D x 8 D projects compensate to a large extent for the denser spacing with the projects, such that the annual energy production is only slightly less (about 1%) than that for the 10 D x 12 D projects which cover almost twice the total area.

Note that the capacity factors and potential annual energy production calculations shown in Table 5 for each leasing area and spacing/development option considering only wake losses. Additional losses due to poor availability, electrical transmission, and other factors can also be expected, which may further reduce the annual energy production by 5%–10%. A fair accounting of net capacity factor, an important metric used by wind developers, would include these losses as well.

4.9 Qualitative Considerations

There are several other criteria that could influence the perceived value of each leasing area for development and the ability to develop the New Jersey area of analysis, but these criteria, such as fisheries, military use, ecological impacts, and traffic, were not considered in the final analysis by NREL and therefore did not influence the delineation strategy.

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 the western-most parts of all the leasing areas are approximately the same distance from shore, which would tend to equalize the impact of distance to shore. No consideration was given to the possibility that turbines located closer to the shore could pose a visual impact concern, and it is uncertain if this could potentially become an issue.

Most developers focused on the southern or middle OCS blocks of the New Jersey WEA, and the northern- and western-most areas showed the lowest degree of interest. Concerns were expressed regarding traffic in that area, military operations, visual impacts, fisheries, or existing cables.

Most developers mentioned that their evaluation was based on a combination of studies. They did not always specify why they came to a conclusion for a certain project area, and it is likely that they will revise their decision depending on competition and prices for blocks. Many also noted that further studies will be necessary to finalize their preferred project area.

Finally, developer inputs received through the Call reviews were somewhat informative but did not provide enough detailed project information to impact NREL's leasing area delineation analysis or final recommendations.

5 Key Findings

Below are the key findings of the NREL analysis and considerations for BOEM, policy makers, and stakeholders involved in the New Jersey offshore wind energy development process.

- The maximum capacity of the entire NJ area of analysis, using 10 D x 12 D spacing and internal buffers between leasing areas, was found to be between 3,100 MW and 3,400 MW, depending on the number of leasing areas. The NJ area of analysis is capable of supporting at least four leasing areas with equitable divisions using reasonable assumptions that would accommodate wind projects of at least 500 MW per area.
- Diagonal (roughly northwest-southeast) delineations proved to be the most efficient strategy for dividing the NJ area of analysis because they resulted in the shortest delineation boundaries which maximized the developable area. Higher potential wake losses in the middle leasing areas were compensated for by adding additional area to allow for greater flexibility when placing internal buffers.
- Bathymetry of the NJ area of analysis is generally favorable in all leasing areas and is not expected to affect the leasing value of one area relative to another. Most leasing areas would have over 90% of the water in depths less than 30 meters.
- Average annual wind speed for the NJ area of analysis ranged from 8.4 m/s to 8.6 m/s in all leasing areas assessed. This corresponds to a range of gross capacity factors between 45.4% and 47.0%.
- Total energy losses from wake effects in the fully developed baseline case of 10 D x 12 D spacing in all (four) leasing areas were reduced from a range of 7% to 10% to a range of 5% to 7% when project size was limited to 500 MW in each leasing area.
- The grid orientation angle was found to have only a minor impact on array efficiency using the OpenWind model with 10 D x 12 D spacing and 10% turbulence intensity. The best grid orientation angle was 75 degrees for the 10 D x 12 D spacing.
- Wake losses increased with decreasing turbine spacing. For the scenario of developing four leasing areas to their maximum potential, wake losses averaged 6%–9% for 10 D x 15 D spacing, 7%−10% for 10 D x 12 D spacing, and 11%−14% for 8 D x 8 D spacing. For all spacing scenarios, the highest wake losses were in the middle areas.
- If the projects were limited to 500 MW developed in all four leasing areas, wake losses were significantly reduced. The average wake losses for the area of analysis are 6.6% for 10 D x 12 D spacing and 7.3% for 8 D x 8 D spacing. However, the area required for an 8 D x 8 D project is only about half that for a 10 D x 12 D project.
- Wake effects from one leasing area to another will play a significant role in siting offshore wind turbines in the NJ area of analysis. However, NREL researchers found that wake losses from neighboring wind projects within the NJ area of analysis were less than 30% of the total array losses. Most wake losses are generated internally to a given project.
- The optimal number of leasing area delineations (i.e., two, three, or four leasing areas) may depend on requirements for development capacity or project size that may be dictated by

administrative or political policy. This report does not attempt to interpret potential constraints related to the New Jersey offshore wind legislation (New Jersey 2010).

- The four leasing area option provides ample development potential to allow for a commercial-scale project in each leasing area with a maximum potential for the greatest diversity of developers. More developers could result in more rapid concurrent development of the entire WEA.
- The wake analysis in this report is coarse by industry standards and it is recommended that prospective lessees investigate wake losses more rigorously before judging the values of these leasing areas. An 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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