State of New Jersey

New Jersey Board of Public Utilities (NJBPU)
Bureau of Conservation and Renewable Energy & Office of Clean Energy

New Jersey Clean Energy PROGRAM™

<u>Project Title</u>: ***Atmospheric/Oceanic Analyses and Predictions to Support the Wind Energy Development Process Defined in NJ's Offshore Wind Economic Development Act, NJBPU's Offshore Wind (OSW) Renewable Energy Rules (N.J.A.C. 14:8-6), and the Offshore Wind Energy Development Criteria Presented in the NJ Energy Master Plan*** **(Final Report for the Period 24 Jun 2013-23 Jun 2014).**

RUTGERS MARINE & COASTAL SCIENCES

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Aug 2014

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Abstract

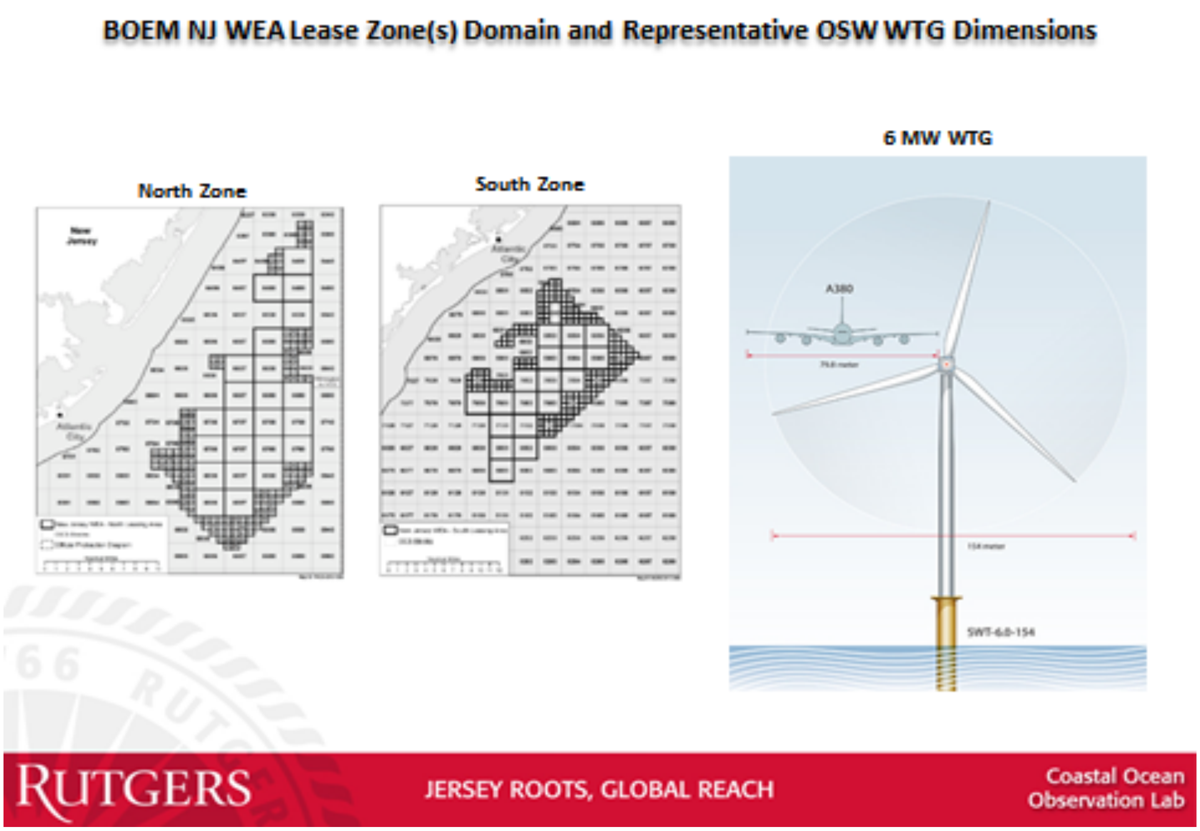
Once proposed offshore wind power generating systems become operational, substantial wind energy penetrations into the power grid can be expected for densely populated coastal areas (e.g., NJ) where energy demand is high. The *variability* in the wind resource at atmospheric heights representative of offshore wind turbine dimensions (e.g., 100m hub heights) in conjunction with varying energy demand were analyzed to provide the necessary information needed to evaluate power production potential along with the associated economic issues associated with offshore wind energy development. Therefore, the "risks" and relevant costs resulting from the variability of wind power production and uncertain demand requirements can be significantly reduced by utilizing a representative analytical/predictive program designed specifically for each offshore wind energy site and supporting facilities associated with the transmission/distribution infrastructure. Such a program using an advanced high-resolution 3-D offshore wind modeling program, which is based on the accepted WRF model, was developed by the Rutgers University Coastal Ocean Observation Laboratory (RU-COOL) with funding provided by the NJ Board of Public Utilities (NJBPU). The current phase (*Phase II*) of the Rutgers/NJBPU offshore wind energy study utilized the wind resource assessment results that were compiled during *Phase I* of the project. These validated results were used to estimate potential wind power production that could be achieved from "hypothetical" wind parks located within the BOEM NJ WEA (Wind Energy Area), which is the area offshore from the NJ coast that is designated for wind energy development. Installed Capacities of 1,100 MW, 2000 MW, and 3000 MW, which coincide with the values presented in the NJ Energy Master Plan and Offshore Wind (OSW) energy regulations, were used for the potential wind power production projections. Various wind turbine generator (WTG) array spacing scenarios were used to account for the "typical" loss factors associated with WTG turbulent wake effects. In addition to turbulent wake effects, other losses attributed to WTG design/transmission constraints were considered in the estimation of Net Capacity Factors (NCFs) that were calculated to be approximately 35 percent. Also, the impacts of the sea breeze circulation and coastal storms on the offshore wind resource were considered in the assessment. The resultant hourly data set was provided to the Rutgers Center for Environmental, Energy, and Economic Policy (CEEEP) for input into their energy and economic models to determine the overall viability of NJ's offshore wind energy development endeavors.

The current and previous offshore wind energy studies will be used as a basis to enhance the forthcoming study (*Phase III*) that will focus specifically on the two BOEM NJ WEA Lease Zones, which are uniquely affected by the sea breeze circulation and other offshore wind flow perturbations (e.g., coastal storms). These wind resource perturbations will be analyzed in detail to determine their impact on power production, especially during periods of "peak" energy demand. Furthermore, the actual site characteristics, proposed wind turbine generator (WTG) array configurations, and specifications of the WTGs selected to be installed and operated within the BOEM NJ WEA will be used for the analyses. Therefore, the offshore wind resource assessments along with associated predicted power production estimations and economic evaluations will cost-effectively support unbiased decisions relevant to NJ's offshore wind energy requirements and regulations.

BPU OSW IMCS/CEEEP Final *Phase II* Report (24 Jun 2013-23 Jun 2014)

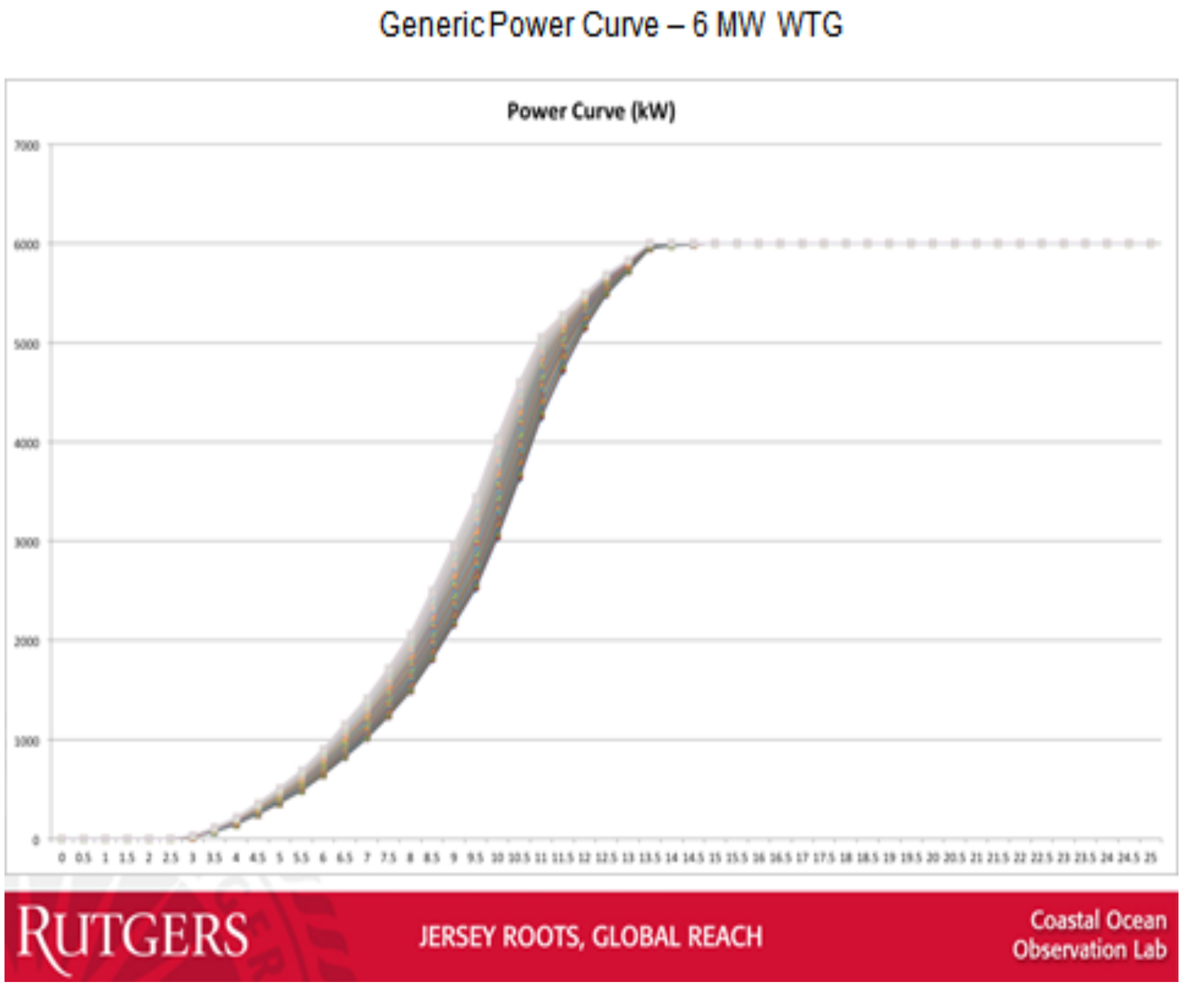
Introduction

The results of the RU Institute of Marine and Coastal Sciences (IMCS) offshore wind (OSW) resource analysis project for the period **24 Jun 2013-23 Jun 2014 (*Phase II*)** are based on in-depth atmospheric simulations that utilized our innovative RU-WRF modeling program. Previous modeling endeavors were run at a horizontal grid spacing of 3 km. We increased the 3 km resolution to 1 km for the current analysis, which provided a more "site-specific" study that more realistically coincided with the dimensions of the lease blocks contained within the BOEM NJ WEA. Representative meteorological parameters used for current modeling input were extracted from an archive of extensive high-resolution verified mesoscale RU-WRF model data that were compiled during the previous RU IMCS offshore wind resource study (i.e., ***Phase 1:* 14 Apr 2011-13 Apr 2013** (*Glenn and Dunk, 2010*)). Additionally, this modeling data set was updated to include the most recent data acquired from validated meteorological towers and buoys along with high-resolution sea surface temperatures (SSTs) derived from the RU IMCS Infrared (IR) satellite "de-clouded" product. RU-WRF model results for hourly wind resource variables and resultant power production parameters for "hypothetical" offshore wind parks located in both the proposed North and South BOEM NJ WEA Lease Zones were provided to the RU Center for Energy, Economic, and Environmental Policy (CEEEP) for input into their energy and economic models. BOEM NJ WEA lease zone domains along with representative offshore wind turbine generator (WTG) dimensions used for this analysis are respectively shown in the following figures:



Discussion

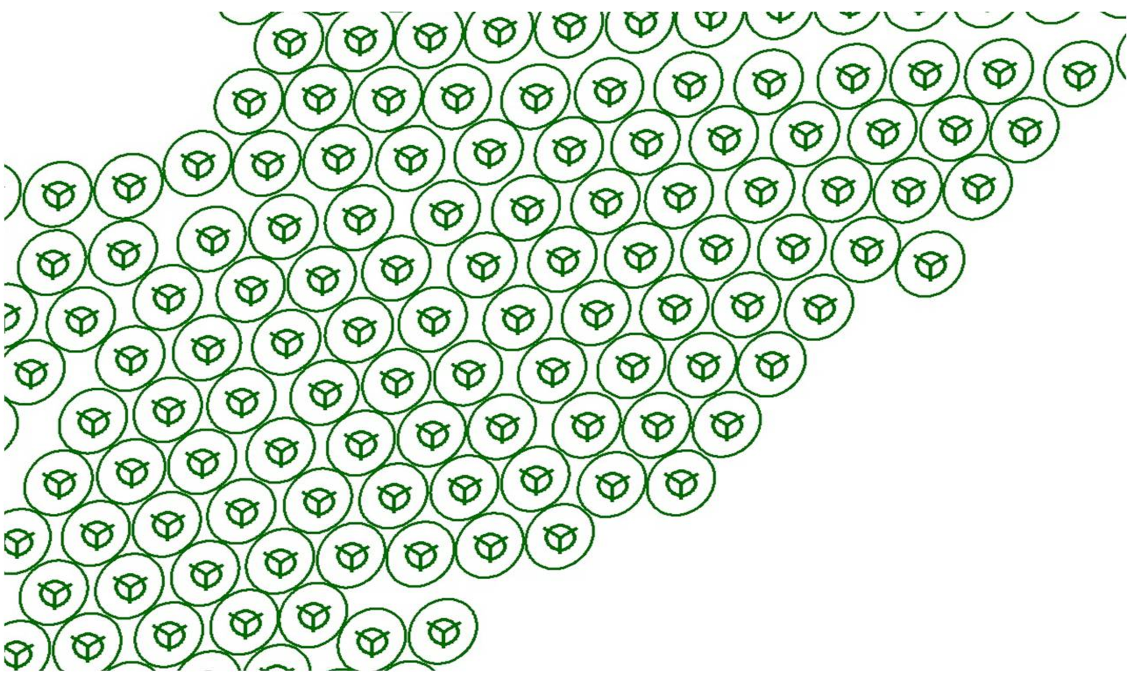
The RU-WRF modeling program utilizes a “generic” power curve developed from the specifications for several offshore 5 MW, 6 MW, and 7 MW WTGs. This generic WTG power curve provides the most representative and unbiased information for our modeling scenarios. Therefore, along with the updated meteorological data, the results of the modeling runs presented in this report are based on the derived “generic” WTG power curve, which is shown in the following graph:



Hypothetical WTG OSW parks were arranged in arrays designed to accommodate 8D X 10D, 10D X 12D, and 10D X 15D spacing between individual generators, where D is the rotor diameter. The “hypothetical” WTG arrays were configured for installed wind energy capacities of approximately 1100 MW, 2000 MW, and 3000 MW for the total BOEM NJ WEA. These “total” installed capacity factors were divided evenly between the North and South BOEM NJ WEA Lease Zones. The stated capacity factors were selected to coincide with the capacity factors suggested for offshore wind energy development as presented in NJ’s Energy Master Plan, the NJ OSW Economic Development Act, NJ’s Offshore Wind Energy Development Application Regulations, BOEM’s NJ WEA dimensional specifications, and associated offshore wind energy development policies and procedures.

The same WTG spacing (i.e., 10D X 12D) used for the previous model runs was also included in the current analysis presented in this report. WTG manufactures have suggested that the "optimum" WTG spacing matrix should be 8D X10D for offshore applications. Our selected WTG 10D X 12D spacing criteria is based on the RU-WRF modeling results that include the effects of interactions between the unique characteristics of NJ's coast and offshore areas, marine atmospheric boundary layer (MABL) dynamics, and resultant turbulent wake effects among individual WTGs. The suggested 8D X 10D spacing is based on actual offshore WTG operations in various locations in Europe where wind flow patterns and turbulence interactions are different than those encountered along the coastal/offshore areas associated with the eastern US. The 10D spacing is oriented approximately W to E and the 12D spacing is oriented approximately SW to NE to coincide with the most frequently occurring wind directions along with wind vectors produced by local wind flow patterns (e.g., the sea breeze circulation) that are encountered over the NJ WEA. The 10D X 15D spacing scenario may be too conservative and may prove not to be a viable option for NJ's offshore wind development initiate. However, to compare WTG spacing options, we included all three WTG array scenarios for each of the three selected installed capacity factors.

Although, all of the scenarios produced similar results, it appears that the 10D X 12D WTG spacing scenario appears to be the most efficient. Additionally, when local wind flow patterns are taken into account, "staggered" WTG placement within the array should be considered to obtain the most effective utilization of both the general offshore wind resource and local wind resource perturbations. Based on the previous discussion, a suggested simulated WTG array spacing is displayed below.



Hypothetical WTG Array showing 10D X12D spacing with a "staggered" configuration to account for Prevailing Winds along with the effects of Local Wind Flow Patterns (e.g., the Sea breeze Circulation).

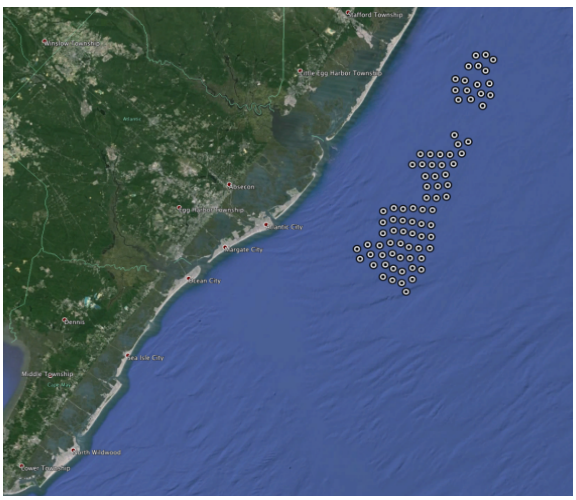
The modeling scenarios are summarized in the following bullet items:

- 1100 MW – Total BOEM NJ WEA (~550 MW North Zone; ~550 MW South Zone).
- 2000 MW – Total BOEM NJ WEA (~1000 MW North Zone; ~1000 MW South Zone).
- 3000 MW – Total BOEM NJ WEA (1500 MW North Zone; 1500 MW South Zone).

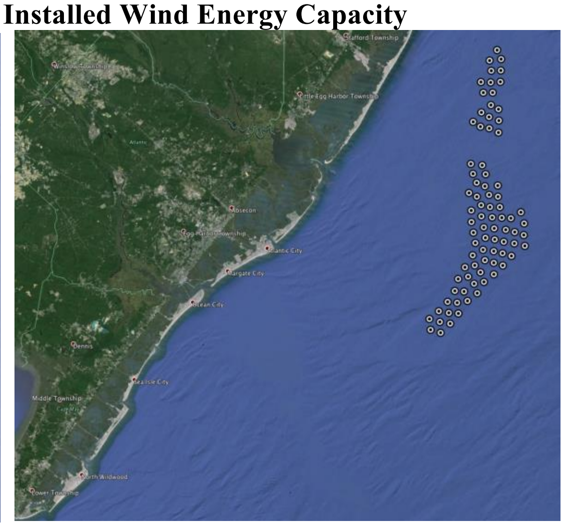
Simulated Offshore WTG Arrays

Proposed BOEM NJ WEA Lease Zone locations, simulated WTG array configurations, and individual WTG positions within the arrays are shown in the following images:

BOEM NJ WEA with~1100 MW Installed Wind Energy Capacity



BOEM NJ WEA North Lease Zone (NW Sector)



BOEM NJ WEA North Lease Zone (NE Sector)

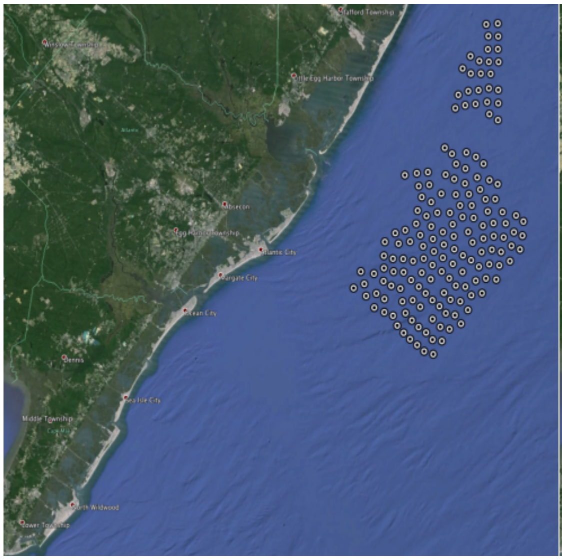
BOEM NJ WEA North Lease Zone with ~550 MW Installed wind energy Capacity

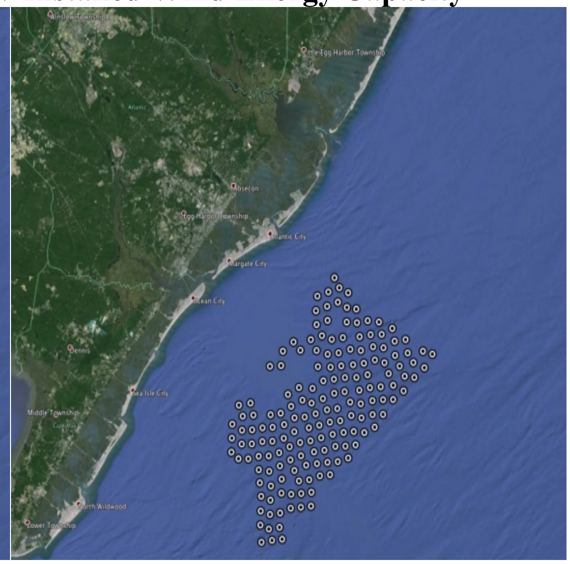
BOEM NJ WEA South Lease Zone (SW Sector)

BOEM NJ WEA South Lease Zone (SE Sector)

BOEM NJ WEA South Lease Zone with ~550 MW Installed Wind Energy Capacity

BOEM NJ WEA with ~2000 MW Installed Wind Energy Capacity

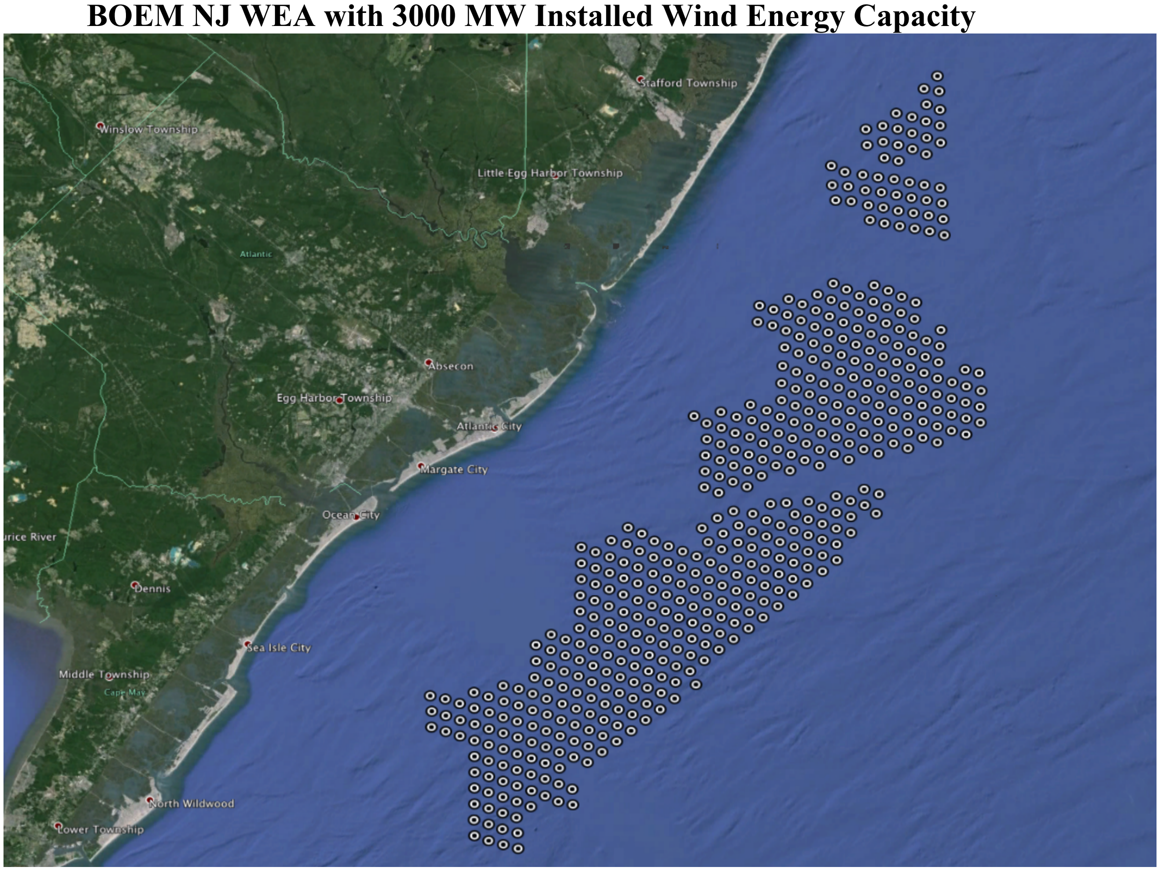




BOEM NJ WEA North Lease Zone **BOEM NJ WEA South lease Zone**

BOEM NJ WEA North and South Lease Zones, each with~1000 MW Installed Capacity

BOEM NJ WEA with 3000 MW Installed Wind Energy Capacity



BOEM NJ WEA North and South Lease Zones

BOEM NJ WEA North and South Lease Zones with a total of 3000 MW Installed Capacity

Results

General Offshore Wind Resource Characteristics

RU-WRF model results were compiled and analyzed for the period June 2011 through May 2014. These results are based on the averages of the selected WTG spacing scenarios and associated installed capacity factors that are encompassed by the entire BOEM NJ WEA. The hourly, monthly, and annual results are provided in the attached EXCEL spreadsheet. The spreadsheet includes the wind resource and power production results for each installed capacity factor (i.e., 1100 MW, 2000 MW, and 3000 MW) along with associated WTG spacing scenarios (i.e., 8D X 10D, 10D X 12D, and 10D X 15D).

Average hourly, monthly, and annual offshore wind speeds at 100m hub heights above mean sea level (AMSL) representative of offshore wind WTGs that will potentially be installed within the BOEM NJ WEA are summarized in the following table:

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG
00 - 01	10.12	10.46	10.24	9.60	9.28	8.44	8.19	7.12	7.70	8.34	9.24	9.81	**9.05**
01 - 02	10.20	10.33	10.01	9.65	9.16	8.33	7.96	7.10	7.64	8.72	9.38	9.95	**9.03**
02 - 03	10.01	10.20	9.86	9.74	9.28	8.15	7.73	7.00	7.62	9.24	9.53	10.06	**9.04**
03 - 04	9.94	10.15	9.87	9.74	9.24	8.20	7.82	7.23	7.68	9.45	9.66	10.35	**9.11**
04 - 05	10.07	10.33	9.93	9.79	9.22	8.07	7.58	7.16	7.80	9.45	9.69	10.32	**9.12**
05 - 06	10.03	9.96	9.79	9.75	9.19	7.79	7.42	7.00	7.81	9.44	9.61	10.17	**9.00**
06 - 07	10.04	9.68	9.67	9.64	9.21	7.82	7.24	7.07	7.71	9.49	9.49	10.14	**8.93**
07 - 08	10.04	9.61	9.76	9.41	9.29	7.70	7.01	6.98	7.56	9.15	9.29	10.03	**8.82**
08 - 09	10.04	9.63	10.00	9.14	9.08	7.67	6.86	6.88	7.36	8.97	9.10	10.03	**8.73**
09 - 10	10.10	10.13	10.10	9.22	9.02	7.40	6.62	6.73	7.17	8.71	9.01	9.83	**8.67**
10 - 11	10.45	10.40	10.29	9.25	8.81	7.25	6.46	6.62	6.98	8.40	8.93	9.74	**8.63**
11 - 12	10.60	10.92	10.33	9.19	8.47	7.26	6.51	6.76	6.94	8.12	8.83	9.73	**8.64**
12 - 13	10.40	10.93	10.40	9.22	8.33	7.02	6.49	6.64	6.85	8.07	8.81	9.66	**8.57**
13 - 14	10.51	11.02	10.53	9.07	8.32	6.70	6.27	6.44	6.83	7.93	8.64	9.73	**8.50**
14 - 15	10.66	10.97	10.55	8.89	7.97	6.44	6.23	6.52	6.73	7.86	8.71	9.67	**8.43**
15 - 16	10.57	10.82	10.31	8.77	7.69	6.10	5.98	6.30	6.61	7.74	8.58	9.50	**8.25**
16 - 17	9.98	10.37	10.27	8.41	7.43	5.95	5.74	5.93	6.45	7.70	8.36	9.54	**8.01**
17 - 18	9.63	10.01	9.68	8.25	7.74	6.21	5.75	5.87	6.34	7.54	8.22	9.42	**7.89**
18 - 19	9.42	9.49	9.85	8.39	8.35	6.70	6.02	6.06	6.30	7.48	8.17	9.52	**7.98**
19 - 20	9.38	9.45	9.89	8.56	8.69	7.42	6.66	6.44	6.41	7.65	8.14	9.35	**8.17**
20 - 21	9.69	9.72	10.02	8.88	9.16	7.87	7.25	6.86	6.65	7.87	8.26	9.64	**8.49**
21 - 22	9.97	10.02	10.23	9.24	9.35	8.29	7.73	7.23	6.95	8.01	8.51	9.85	**8.78**
22 - 23	10.10	10.25	10.31	9.34	9.55	8.37	8.10	7.43	7.21	8.24	8.75	9.83	**8.96**
23 - 24	10.39	10.00	10.48	9.55	9.71	8.37	8.32	7.52	7.38	8.33	8.91	10.05	**9.08**
AVG	**10.10**	**10.20**	**10.10**	**9.20**	**8.81**	**7.48**	**7.00**	**6.79**	**7.11**	**8.41**	**8.91**	**9.83**	**8.66**

Average Wind Speeds at 100m AMSL for the BOEM NJ WEA (Jun 2011-May 2014)

Wind resource data derived in the preceding table were compared to wind speed climatology (i.e., long-term average values (climatological "normals"), which are based on the most recent 20-yr period of valid data compiled from representative coastal/offshore monitoring facilities). The standard Climatological Normal is based on a 30-yr record that is updated every decade. However, the 20-yr average ("normal") used for this study is consistent with the climatological time frame used by the utility industry, which is generally based on a 20-yr "rolling" annual average (i.e., the "normal" is updated annually using the most recent 20-yr period of record). The previous table was condensed to show monthly and annual averages along with the long-term climatology "normals" for 100m WTG hub height wind speeds estimated to be encountered over the BOEM NJ WEA. The condensed table is presented on the proceeding page.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG
2011						6.11	6.39	6.99	6.66	7.80	8.84	10.29	7.59
2012	11.47	11.57	11.08	8.98	8.31	7.40	6.78	6.27	6.96	8.72	8.78	9.16	8.79
2013	9.03	9.59	9.39	9.29	9.16	8.93	7.82	7.09	7.72	8.72	9.11	10.03	8.82
2014	9.79	9.45	9.84	9.31	8.98								9.47
AVG	10.10	10.20	10.10	9.20	8.81	7.48	7.00	6.79	7.11	8.41	8.91	9.83	8.67
Long-term	11.65	10.71	8.94	7.54	6.56	6.41	6.48	6.96	9.08	9.87	10.02	11.22	8.78

Average Monthly/Annual Wind Speeds @100m AMSL over the BOEM NJ WEA for the period Jun 2011-May 2014 along with Long-Term Wind Speed Climatology.

Using the wind resource data compiled during the Jun 2011-May 2014 study period, an analysis of wind speed provided in the preceding tables for the BOEM NJ WEA produced the following statistics for 100m WTG hub heights:

- Wind speeds were slightly below "normal" when averaged over the entire study period. The average annual wind speed for the study period was 8.67 m/s; the current climatological ("normal") annual wind speed is 8.78 m/s.

- Wind speeds during the "Summer Primary Peak Energy Demand Period" (i.e., Jun-Sep) were estimated to be slightly below "normal". Average wind speeds during the summer peak demand period were 7.10 m/s; the current climatological "normal" is 7.23 m/s.

- Wind speeds during the "Winter Secondary Peak Energy Demand Period" (i.e., Dec-Mar) were estimated to be slightly below "normal". Average wind speeds during the winter peak were 10.06 m/s; the current climatological "normal" is 10.63 m/s.

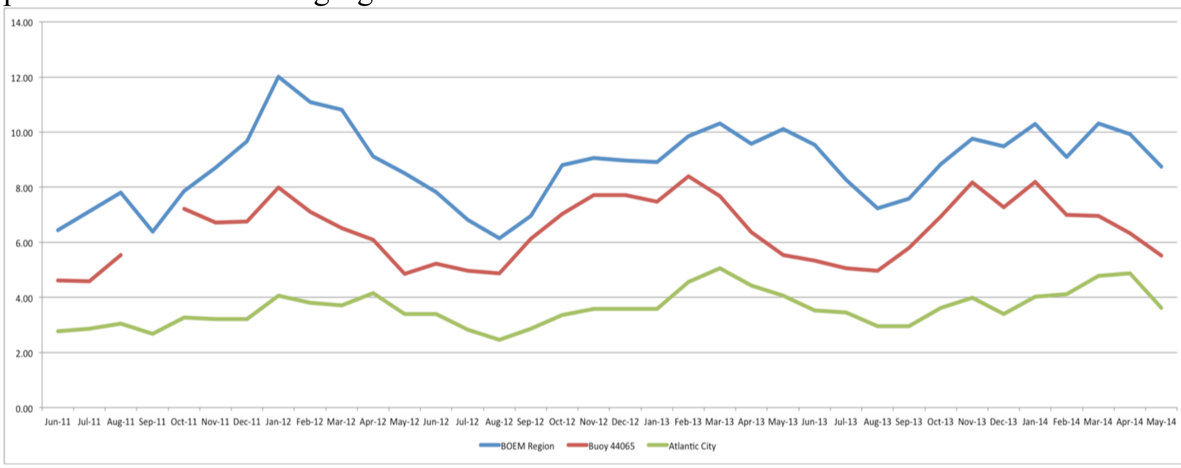
- Wind speeds were above "normal" during the 2012 winter period when wind speeds averaged 10.82 m/s; the current "normal" for the winter period (Dec-Mar) is 10.63 m/s.

- Energy consumption associated with the PJM service territory that occurred during the 2014 "Winter Peak Energy Demand Period" was substantially higher than normal. Therefore, if offshore wind parks were operational during the indicated period, wind energy would have been a substantial contributor for alleviating the "stress" on both conventional generation operations and transmission/distribution systems.

- Wind speeds (determined for the "Spring Shoulder Months" Apr-May (9.01 m/s) were significantly above normal (7.05 m/s); average wind speeds (8.66 m/s) were significantly below normal (9.95 m/s) for the "Fall Shoulder Months" Oct-Nov.

- Note that minimal changes in wind speed (e.g., $\pm$1.0 m/s) could produce significant changes in power production since power production is directly proportional to the cube of the wind speed (m/s^3).

A “time series” of wind speed was produced for NJ’s coastal and offshore areas using monitoring and modeling data from Atlantic City’s (ACY) Pomona, NJ 10m tower, NOAA’s Cape May buoy (the anemometer is installed ~5m above the sea surface), and a “Virtual” 100m meteorological tower centrally located within the BOEM NJ WEA (data derived by the RU-WRF model). This analysis is graphically presented in the chart provided in the following figure.



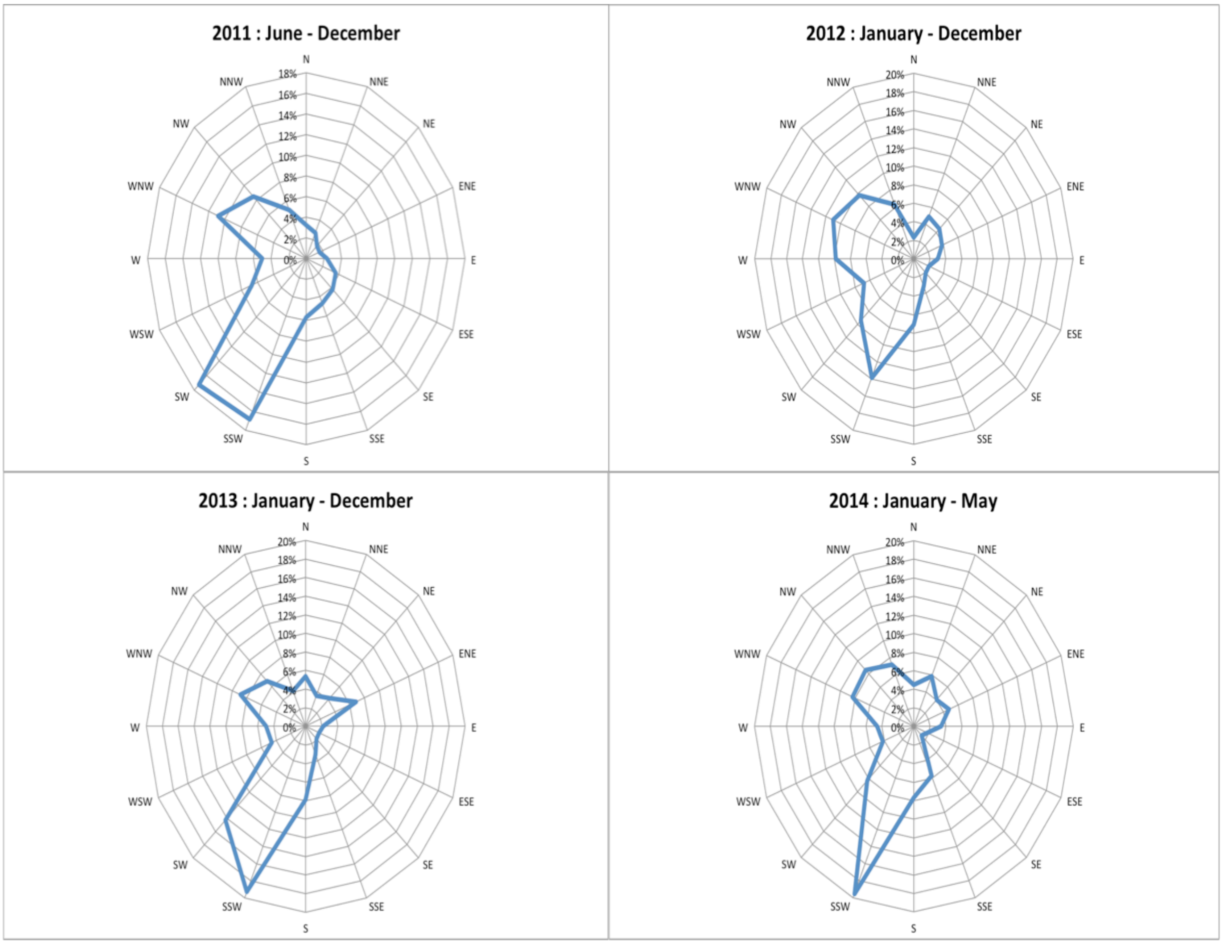
Wind Speed (m/s) Time Series (Jun 2011-May 2014) Representative of NJ’s Coastal/Offshore Areas

The wind speed time series graphs provide the following “trends” and concepts regarding NJ’s coastal/offshore wind resource:

- Generally, offshore wind speeds are significantly higher (>2.0-4.0 m/s) than onshore wind speeds.
- Generally, offshore wind speeds significantly increase with height (e.g., during Dec 2011 average offshore wind speeds @5m and 100m were respectively ~4m/s and 12m/s).
- It is apparent that seasonal fluctuations in wind speed are more prominent offshore when compared to wind speeds over inland areas.
- Average wind speeds during the study period are highest (~10.1m/s) during the winter period (Dec-Mar) and lowest (~7.1m/s) during the summer period (Jun-Sep). Long-Period (climatological “normals”) for the respective winter and summer periods are ~10.6m/s and 7.2m/s. Therefore, offshore wind speeds @100m WTG hub heights that occur over the BOEM NJ WEA should be more than adequate for cost-effective wind power production.

Wind energy production estimates account for loss factors attributed to marine atmospheric boundary layer (MABL) dynamics (e.g., effects of turbulence intensity and wind shear) and estimated mechanical efficiencies of the WTG components. Depending on the convective properties of the air above the sea surface and resultant atmospheric stability, the MABL can extend approximately 100m above the sea surface to near 3km. Therefore, when considering the dimensions of offshore WTGs, WTG structural integrity, and wind power generation efficiencies, the overall performance of offshore WTG arrays will be affected by the physical characteristics and associated dynamics of the MABL.

Wind power production potential frequencies, which are dependent on prevailing wind directions that occur over the BOEM NJ WEA, are provided in the following diagrams. These diagrams were developed from the wind resource data compiled during the four years that comprise the entire study period (i.e., Jun 2011-Dec 2011, Jan 2012-Dec 2012, Jan 2013-Dec 2013, and Jan 2014-May 2014).



Power Production Frequencies for the BOEM NJ WEA that are dependent on Prevailing Wind Direction

The preceding wind power production potential frequency diagrams for the BOEM NJ WEA indicate that the following wind flow sectors are the most conducive for offhsore wind power production:

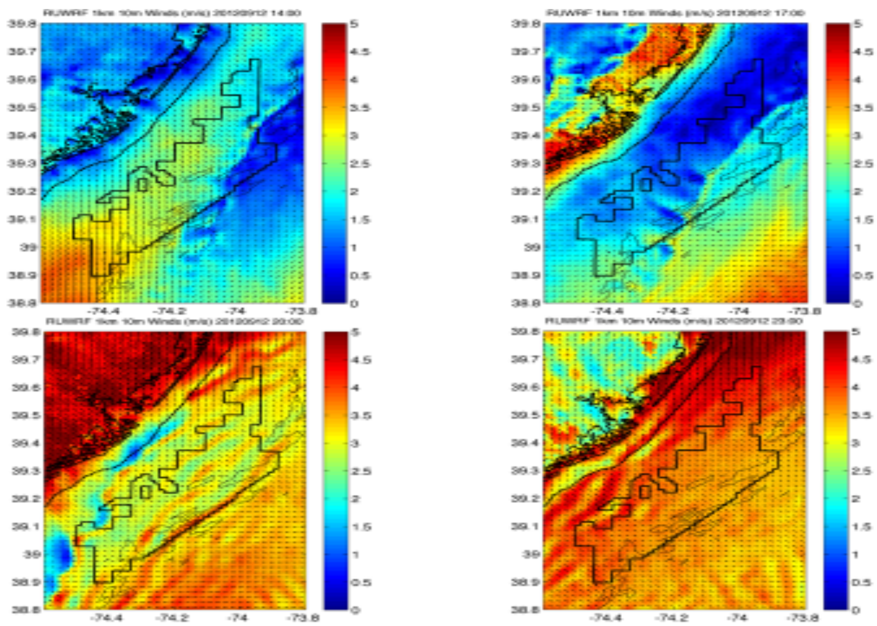
- Prevailing southwesterly winds produce the greatest wind power production potential values with secondary "peaks' resulting from northwesterly and northeasterly wind flow occurrences.

- It appears that significant power production potential resulting from southeasterly wind flow could occur during the spring and summer months resulting from the sea breeze circulation and potential "tropical" or "extra-tropical" storm systems.

Local Offshore Wind Resource Perturbations and Associated Wind Flow Properties

Sea Breeze Circulation

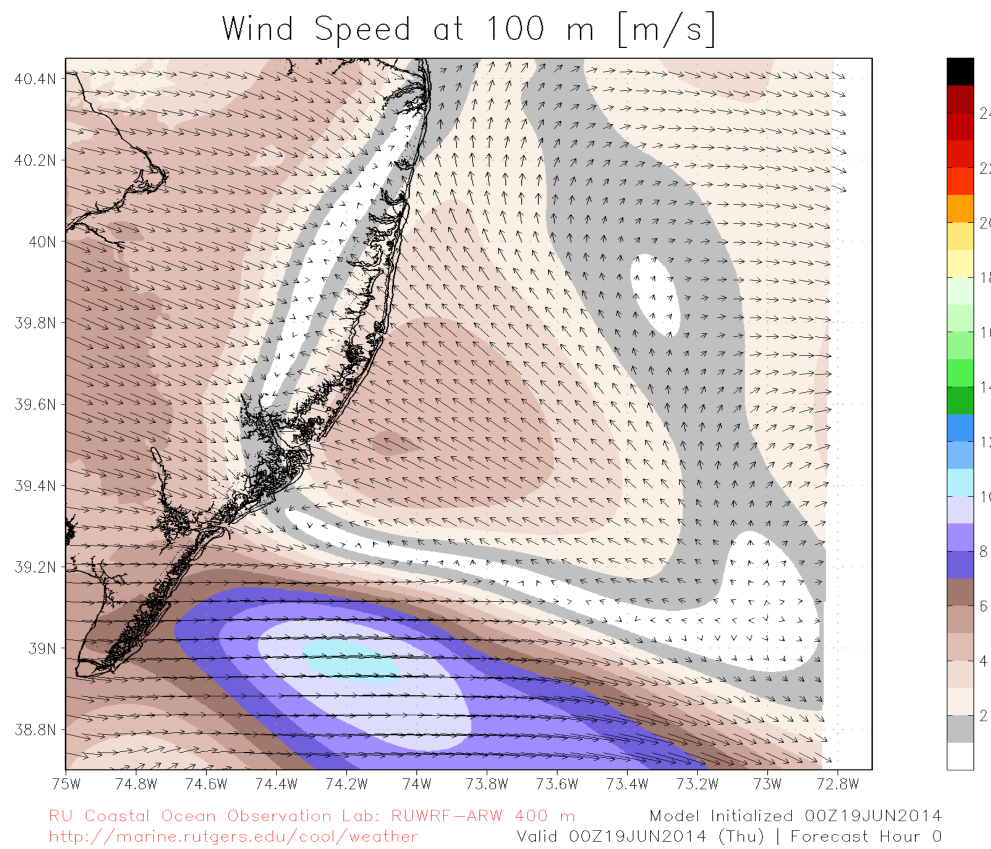
Previous and current analyses of various NJ sea breeze events indicate that the sea breeze circulation exhibits substantial temporal and spatial variability within the BOEM NJ WEA during early afternoon through late evening hours, which coincide with the "Summer Season Peak Energy Demand Period". A progressive time sequence of a selected sea breeze event that occurred over the BOEM NJ WEA is displayed in the following images:



Sea Breeze event that occurred over the BOEM NJ WEA showing both Significant Temporal and Spatial Variability in Wind Speeds (i.e., wind speeds ranged from <0.5 m/s to ~4.5 m/s).

A more recent sea breeze event that occurred during June 2014 was modeled at a 3 km resolution. However, wind flow vectors associated with the observed sea breeze occurrence could not be resolved by the model. The mesoscale model (RU-WRF) was then programmed ("nested") to run at a microscale resolution of 400m. The resultant microscale simulation resolved the sea breeze circulation, which showed that the sea breeze occurred over the northern portion (North Lease Zone) of the BOEM NJ WEA. However, the sea breeze did not develop over the southern portion (South Lease Zone) of the WEA. This simulation agrees with available observations obtained from coastal meteorological towers, CODAR derived sea surface current patterns, and IR satellite SST detection data. The microscale simulation provides similar information regarding offshore wind flow variability that was indicated in the previous mesoscale simulations. However, the microscale simulation shows substantially more detail than the mesoscale simulations. Therefore, sea breeze circulation simulations should be conducted at microscale resolutions that will provide the detailed information required for efficient and effective offshore WTG array design applications, construction activities, and operational procedures. The preceding statement is especially pertinent for the "Summer Season Peak Energy Demand Period".

The microscale sea breeze simulation discussed on the previous page is presented in the following image:



High-Resolution (400m horizontal grid-spacing) Sea Breeze Simulation at 100m AMSL

Referring to the preceding simulation, the following wind resource information can be realized for this particular sea breeze event:

- Wind speeds over the North BOEM NJ WEA Lease Zone ranged from <2m/s to ~6 m/s, which implies that WTGs potentially located within certain portions of the North Zone could be producing power while other WTGs would be idle during this sea breeze event. As the sea breeze propagates farther offshore, WTGs that were idle could start to produce power and WTGs that were producing power may become idle. Therefore, the sea breeze circulation is considered a dynamic process with wind flow vectors that change both temporally and spatially. Note that most offshore WTGs will *not* start to produce power until wind speeds exceed ~3.0 m/s (~6.7 mph) (i.e., *self-start or cut-in speed*).

- Wind speeds over the South BOEM NJ WEA Lease Zone ranged from ~4m/s to ~10m/s, which implies that most WTGs potentially located in the South Zone would be producing power during the indicated sea breeze occurrence.

- Winds speeds within the potential “buffer” area that would separate the North and South BOEM NJ WEA Lease Zones are indicated to be light and variable (e.g., < 1m/s to ~2m/s).

Coastal Storms (Tropical, Extra-Tropical, and Northeaster Storm Events)
NJ's coastal storms have a substantial impact on the offshore wind resource and the potential production of power produced by offshore WTGs. Furthermore, these storm systems are associated with wind speeds that are significantly higher than normal, which could result in both WTG shutdown and possible structural damage. Sustained wind speeds during these storms could be greater than 25m/s (>56 mph), which could be detrimental to the structural integrity of the WTGs. Consequently, most offshore WTGs are designed to *curtail* operations when sustained wind speeds are ≥ 25m/s (i.e., *shut-down or cut-out speed*). Therefore, offshore WTG design specifications should coincide with or surpass IEC codes (i.e., WTG design criteria should be compatible with sites that have the following wind resource criteria):

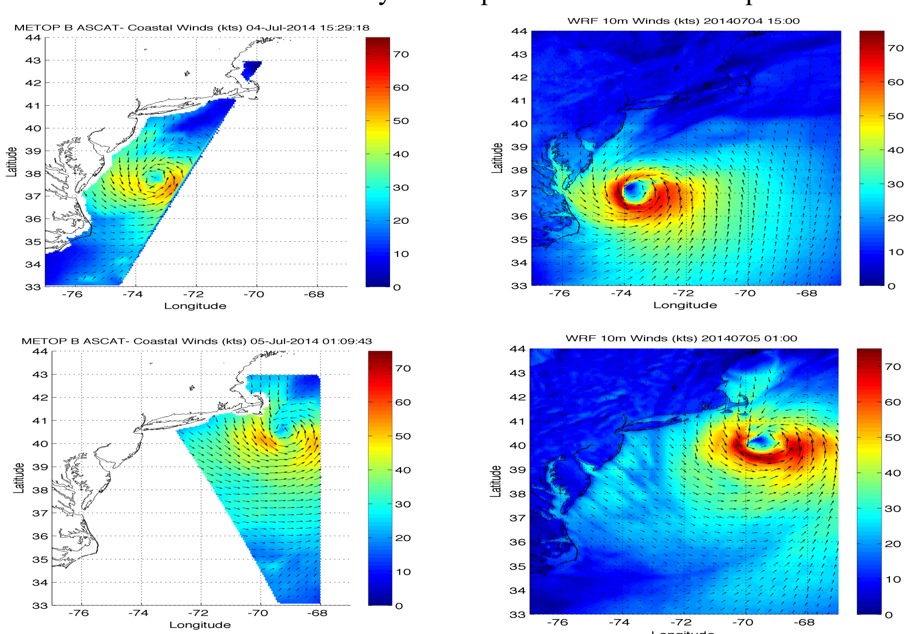
- The site being evaluated for offshore wind energy development has a ≥ 2% probability of 10-min average maximum sustained wind speeds that are ≥50m/s (~112mph) and wind gusts averaged for 3-sec can achieve speeds of ≥70m/s (~157mph).

    - The average maximum 50-yr wind speed is ~= 50m/s (based on a 10-min average).

    - Extreme 50-yr wind gusts is ~= 70m/s (based on a 3-sec average).

- Based on NJ's severe storm climatology, the IEC codes may be sufficient when considering average maximum wind speeds along with extreme wind gusts that will be used for WTG design criteria. Generally, the adverse impact of NJ's severe coastal storms is caused more from strong wave/current action, storm surge, and flooding than from wind.

The following images were derived for Hurricane "Arthur" that occurred during July 2014. The RU-WRF model was used for the analysis and prediction of Arthur's path and intensity.



The above images of Hurricane Arthur were derived from the Advanced Scatterometer (ASCAT) Satellite data (left images) and the RU-WRF model results at a 6km resolution (right images).

The four images presented on the preceding page provide information that are relevant to Hurricane Arthur's track and intensity. These images indicate that Arthur would have had a substantial effect on NJ's offshore wind resource and subsequent power production if WTGs were operational during the time when the storm was in near proximity to the BOEM NJ WEA. The results of the Arthur analysis are summarized as follows:

- Arthur's eye can be seen in both the ASCAT and RU-WRF simulation imagery.

- Track/positioning of Arthur closely agrees with both the ASCAT and RU-WRF model results. These results also agree with the National Hurricane Center's (NHC) determination of Arthur's eye position.

- Referring to the images on the preceding page, the NHC's estimation of intensity using available maximum sustained 10m wind speeds were between 75 and 85 knts (38.6 m/s and 43.7 m/s (left top image)) and ~65 knts (33.4 m/s (left bottom image)). The RU-WRF model simulations agree well with NHC's intensity estimations. However, ASCAT winds were not in agreement with either the NHC or the RU-WRF model results. Possible explanations of ASCAT detection of maximum sustained wind speeds, which were 10 to 20 knts < NHC's estimation of maximum sustained wind speeds include:

    - The coarse resolution of ASCAT detected winds cannot resolve small scale wind speed maxima.

    - Rain contamination/attenuation of ASCAT backscatter can produce a negative bias in ASCAT winds. Therefore, heavy rains during tropical cyclone passage would be more likely to produce a larger negative bias in wind speed.

- Sustained maximum wind speeds associated with Arthur were high enough ($\geq$25 m/s) to curtail offshore WTG operations during the period when the storm approached and passed by the BOEM NJ WEA.

The analysis and prediction of hurricanes, northeasters, and thunderstorms with intense lightning and winds are critical when considering offshore WTG construction planning and what procedures need to be developed to ensure personnel safety and, once installed, protection of offshore wind energy systems during severe coastal storm events.

Concluding Remarks and Results

The discussion regarding sea breeze and severe coastal storm events provided representative offshore WTG wind speed criteria for start-up (i.e., critical low wind speed needed to initiate power production) and shut-down (i.e., critical high wind speed used to curtail WTG operations to protect system structural integrity). Hub height wind speeds needed to achieve maximum power (MW) production for representative offshore WTGs is ~14m/s. Once this wind speed is obtained, maximum generation output will become constant regardless if wind speeds become greater than the critical value (e.g., >14m/s). The critical wind speed values for start-up, shut-down, and maximum power production were determined from the "generic" WTG power curve that was derived from offshore WTG design specifications provided by the offshore WTG manufacturers. With the advancement of offshore WTG technology, the current wind speed criteria will probably change as a result of improved WTG component design along with enhanced efficiency and subsequent increased productivity of WTG operations.

Average wind speeds over the BOEM NJ WEA at 100m AMSL, wake loss percent, and net capacity factors (NCFs) determined for the study period (i.e., Jun 2011-May 2014) are presented in the below table. The values stated in the table were determined using the following criteria:

- Wind speed @100m WTG hub height was considered to be representative for offshore WTGs.
- Wake loss is the modeled reduction in power production resulting from turbulent wake impacts among individual WTGs within the specified "hypothetical" WTG array.
- The remaining capacity factor reductions (i.e., NCF loss resulting from equipment losses (e.g., transmission cable resistance; WTG physical constraints), and environmental factors (e.g., wind shear and site turbulence)) were based on assumptions used by the wind energy industry.

The preceding parameters were calculated for each of the modeled WTG array scenarios that could potentially be located within the BOEM NJ WEA. These WTG array scenarios include: Installed capacity factors of 1100 MW, 2000 MW, and 3000 MW, each with 8D X 10D, 10D X 12D, and 10D X 15D WTG spacing configurations (where, D=the WTG rotor diameter).

Installed Wind Power Generation Capacity (MW) : WTG Array Spacing	***Average Wind Speed*** **(m/s)**	***Turbulent WTG Wake Reduction*** **(%)**	***Net Wind Power Generation Capacity Factor*** **(NCF %)**
1100 MW: 8DX10D	**8.95 m/s**	**5.93 %**	**36.0 %**
1100 MW: 10DX12D	**8.93 m/s**	**5.47 %**	**35.6 %**
1100 MW: 10DX15D	**8.91 m/s**	**5.39 %**	**35.6 %**
2000 MW: 8DX10D	**8.70 m/s**	**7.18 %**	**35.3 %**
2000 MW: 10DX12D	**8.66 m/s**	**6.65 %**	**34.9 %**
2000 MW: 10DX15D	**8.68 m/s**	**6.32 %**	**35.0 %**
3000 MW: 8DX10D	**8.41 m/s**	**7.90 %**	**35.0 %**
3000 MW: 10DX12D	**8.36 m/s**	**7.52 %**	**34.5 %**
3000 MW: 10DX15D	**8.36 m/s**	**7.31 %**	**34.6 %**

BOEM NJ WEA Average Wind Speeds @100m AMSL,
WTG Turbulent Wake Loss Factors, and WTG Array NCFs.

The results presented in the table on the previous page provide the following realistic information and assumptions regarding offshore wind energy development associated with the BOEM NJ WEA.

- The overall average 100m wind speed (8.66 m/s) derived from the average wind speeds determined for each modeling scenario coincides exactly with the average 100m wind speed (8.66 m/s) calculated for the entire BOEM NJ WEA.

- The RU IMCS recommended Maximum Installed Capacity for the entire BOEM NJ WEA is 3,000 MW, which closely concurs with BOEM's suggested 3,400 MW Maximum Installed Capacity value (Musial et. al. (2013)).

- The RU IMCS estimated average Net Capacity Factor (NCF) of 35% for the entire BOEM NJ WEA is less than the estimated 40% NCF provided by BOEM in the Public Sale Notice (PSN), which includes the procedures for the auction of NJ's offshore Lease Zones designated for offshore wind energy development (BOEM, 2014). Although, the Maximum Installed Capacities (MWs) determined by Rutgers and NREL are similar, the NCFs (%) are substantially different. This difference can be attributed to the following assumptions:

    - The selected make, model, and specifications associated with the WTG proposed to be installed will have power production losses that will vary according to the design criteria established by the individual offshore WTG manufacturers.

    - Physical constraints related to WTG component design and affiliated transmission/distribution systems will affect NCFs.

    - Site-specific restrictions relevant to both the marine and atmospheric environments will contribute to reduced NCFs.

- Basically, with an offshore wind resource that consistently has average wind speeds >8.5 m/s along with a relatively large area (>300,000 acres) that is compatible with construction requirements, the marine environment, and most maritime issues, the BOEM NJ WEA should be very conducive for wind energy development.

Implications

As expected, offshore wind power production values resulting from recent RU-WRF model simulations are similar to previous modeling results, which indicate wind speeds over the North BOEM NJ WEA Lease Zone are slightly higher when compared to wind speeds over the South Lease Zone. Also, as a result of a more intense wind resource that is averaged over an annual period, higher wind power production values will probably occur over areas farther offshore in both the North and South Lease Zones. However, annual averages may not be applicable for certain local wind resource perturbations (e.g., the sea breeze circulation) that can affect wind power production during critical periods of "Peak Energy Demand". Depending on the location of the WTG array and time of occurrence, these wind resource perturbations could result in either a negative or positive impact on electrical power production.

The physical characteristics that cause the differences between the North and South Lease Zones are explained in the report that was submitted to BOEM for their review regarding Lease Zone delineations (Dunk, 2013). This report was included as an attachment to the prior RU IMCS OSW Progress Report (Dunk, 2014).

The current modeling results confirm previous modeling results that suggest the total BOEM NJ WEA can accommodate up to ~ 3000 MW of installed wind power capacity. Once actual offshore WTG arrays begin to be designed, constructed, and become operational, the "optimum" total installed wind power generating capacity for the BOEM NJ WEA could prove to be greater or less than the 3,000 MW to 3,400 MW suggested respectively by RU IMCS and BOEM. Furthermore, the continuing RU-WRF modeling improvements indicate that the results are becoming more consistent along with good agreement with validated monitoring systems. Therefore, our modeling program is probably becoming the most cost-effective method for simulating the actual physical properties of NJ's offshore wind resource.

Forthcoming Modeling Applications

Proposed modeling studies (***Phase III*, 24 Jun 2014-23 Jun 2015**) will utilize the most current version of the RU-WRF model, which will be used to determine specific offshore wind resource characteristics and resultant wind energy production values for the North and South BOEM NJ WEA Lease Zones. The model will be run at higher resolutions when compared to previous model runs for both the meso (2 km to 2,000 km) and micro (<2 km) spatial scales. The "nesting" capabilities of the model will enable the RU-WRF model to be run at horizontal spatial resolutions of 9 km, 3 km, 1 km, and ~300 m. The model runs at these resolutions should produce more realistic and accurate simulations associated with the following offshore wind energy development objectives:

- Provide realistic 3-D representation of the area-specific physical properties of the BOEM NJ WEA wind resource including detailed descriptions of the wind resource associated with the North and South Lease Zones, which are designated for offshore wind energy development.

- Determine Cost-effective and efficient offshore WTG array configurations along with "optimum" spacing between individual WTGs that are located within the array.

- Resolve wind flow vectors associated with the sea breeze circulation, coastal storms, and other local wind resource perturbations. The results of these analyses will be used to ascertain the temporal and spatial impact of these wind flow occurrences on the wind resource and subsequent power production potential.

The proposed RU-WRF modeling programs will utilize actual WTG specifications and site-specific characteristics provided by the wind developer(s) that intend to install WTG systems within the BOEM NJ WEA. These modeling programs will include the following enhancements:

- Large Eddy Simulation (LES) routines will be used to realistically determine:
    - Turbulent wake properties and turbulence intensity within and external of the WTG array.
    - Atmospheric stability/wind shear within and above the MABL and within and external of the sea breeze circulation.

- WTG parameterization schemes will be utilized to determine:
    - Wind flow interactions among WTGs and the resultant impact on power production associated with individual WTGs.
    - Various power production reductions caused by WTG design, connected transmission equipment constraints, and potential site restrictions.

Along with WTG parameterization, LES simulations, and the inclusion of site-specific characteristics, the high-resolution RU-WRF modeling program will continue to incorporate the unique RU-IMCS "de-clouded" Infrared (IR) satellite detected sea surface temperature (SST) algorithm and CODAR derived sea surface current data. Additionally, the RU-WRF model will utilize available in-situ and remote sensing monitoring data that are representative of the BOEM NJ WEA to ensure that modeling results are accurate and representative. Therefore, areas of interest (e.g., upwelling centers and sea breeze circulations) that are prominent along the central/southern NJ coast will be identified. Consequently, a comprehensive understanding of NJ's offshore wind resource and its potential effects on wind energy system design, installation requirements, and subsequent power production will be achieved in an unbiased, efficient, and cost-effective manner.

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