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Maryland's Offshore Wind Power Potential

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Introduction

The United States relies heavily on fossil and nuclear fuels to generate electricity. Renewable energy has become an increasingly attractive alternative to them, given concerns over climate change, difficulty in siting nuclear power plants, health concerns associated with fossil fuel generation, a desire to tap domestic energy resources, and the recognition that green energy development is likely to attract and sustain green jobs. Many states, including Maryland, explicitly encourage renewable energy generation through renewable portfolio standards, which require utilities to acquire a certain percentage of their electric supply from renewable energy sources.

Although only a small fraction of total U.S. electricity is generated from renewable energy sources, in recent years wind power has comprised the second largest fraction of newly installed power, behind natural gas. Wind power has emerged as the renewable energy source of choice in many parts of the country because it is the only proven means to generate utility-scale carbon-free energy in a cost-competitive manner. To date, all of the U.S. wind energy power has been land-based, with much of the generation coming in Texas, California and the Midwest and Great Plains States.

While Maryland will soon be generating land-based wind power, its land-based wind resources are limited (AWS Truewind). For wind power to become a significant fraction of Maryland's electricity supply, it will either need to import land-based wind power from other states and to rely on transmission lines, or look to the sea. Offshore wind power holds much promise for the mid-Atlantic and Northeast states, including Maryland, because it is an abundant resource, proximate to electric load centers (Kempton, et al 2007).

Although no offshore wind turbines have been installed in the Americas, offshore wind power is a proven technology with more than 15 years of operating experience in Europe. Serious interest in offshore wind power in the United States began in 2001 with a proposal for an offshore wind project in Nantucket Sound off Cape Cod, Massachusetts Energy Management, Inc. (aka, Cape Wind). Since that time, many proposals have been put forward in the Atlantic, Gulf, and Great Lakes regions. State Request for Proposals (RFPs) have resulted in binding contracts for offshore wind power in Delaware and Rhode Island, a planned purchase by Maryland for a portion of the power to be generated by the Delaware project, and three proposed developments off of New Jersey. Recently, New York released an RFP for a utility-scale offshore wind project in the Great Lakes (NYPA 2009) and North Carolina announced a small test project of up to three turbines in Pamlico Sound. These states have been at the vanguard of U.S. offshore wind development, but by no means round out the number of states interested in offshore wind. On the Atlantic coast, Maine, Virginia, and Georgia all have varying degrees of interest in offshore wind. Ohio, Michigan, and Wisconsin in the Great Lakes region (as well as Ontario) and Texas in the Gulf are also planning and preparing for offshore wind. With over 2,000 megawatts (MW)

of offshore wind power in various stages of project development, a federal legal regime and policies to encourage renewable energy development in place, the U.S. offshore wind industry is poised to take off.

Detailed resource and feasibility assessments are an important preliminary step that interested states should consider before pursuing further stages of project and economic development. This study represents an initial assessment of the wind resource of the Maryland coast, using methods refined from those published by Dhanju and colleagues (2008). This study considers potential environmental, user, and nautical conflicts, and electric system characteristics and policy in Maryland as they relate to the potential for offshore wind power development.

Section 1. Mapping Areas for Offshore Wind Development in Maryland[1]

1.1 Bathymetry and Turbine Foundation Technology

Understanding the water depth at any potential offshore wind development site is critical for determining the appropriate foundation technology to use, as well as for accurately assessing the cost of installation. In this study, we use three-arc second resolution, satellite bathymetric data made available by the National Oceanographic and Atmospheric Administration (NOAA) to delineate areas of Maryland's coastal waters based on depth (Divins and Metzger 2009). This data is used to illustrate the bathymetry of the Delmarva region. It is notable that this region possesses a gently sloping outer continental shelf, which is in sharp contrast to the quick and steep drop off seen on the Pacific coast. This feature of the Delmarva region allows currently available, shallow water offshore wind technology to be deployed immediately and deeper water technologies to be deployed as they are developed, tested, and become available in the market.

[1] The scope of this analysis is federal and state waters off of Maryland's Atlantic coast. We do not consider development potential within the Chesapeake Bay.

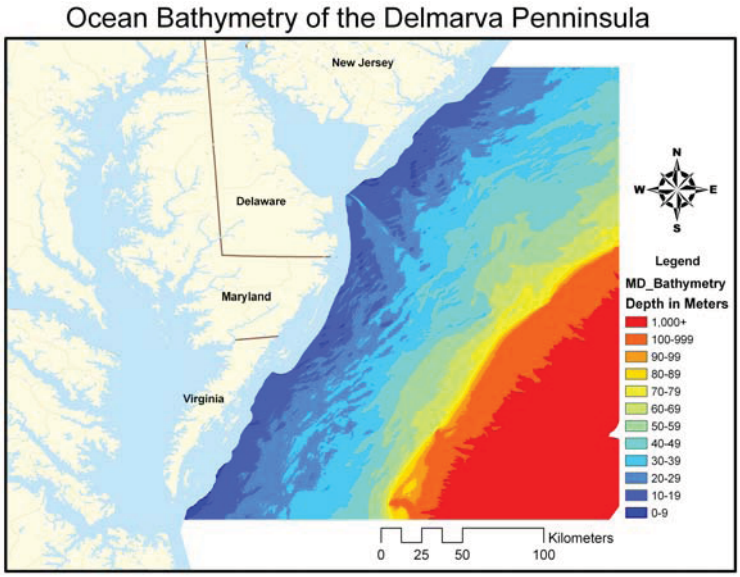

Figure 1. The gently sloping outer continental shelf of the Delmarva Peninsula. Depth shown in meters.

Rather than analyzing Maryland's continental shelf by organizing the data into uniform increments, such as every ten meters shown above, this study approaches bathymetry by associating different water depth ranges to offshore wind turbine foundation technologies. In today's global offshore wind market, the majority of project installations have used the shallow water monopile foundation technology. In Europe, jacket foundation technologies (tripods, quadrapods and lattice structures) have been deployed in small 'pilot' installations over the last few years in waters as deep as 45 meters[2]. However, the jacket design has been validated for up to 100 meters (Haugsøen 2006). One utility-scale floating turbine is operational off the coast of Norway as part of an R&D effort led by StatoilHydro and is designed for depths greater than 120 meters. The University of Maine is planning a small-scale test of floating turbines at depths greater than 60 meters. Figure 2 illustrates categories of offshore wind turbine foundation technology but does not represent an exhaustive list of designs. Within each category of foundations shown, industrial, academic, and government research efforts continue to refine support structures and develop new designs.

[2] See Beatrice and Alpha Ventus projects in Scotland and Germany, respectively.

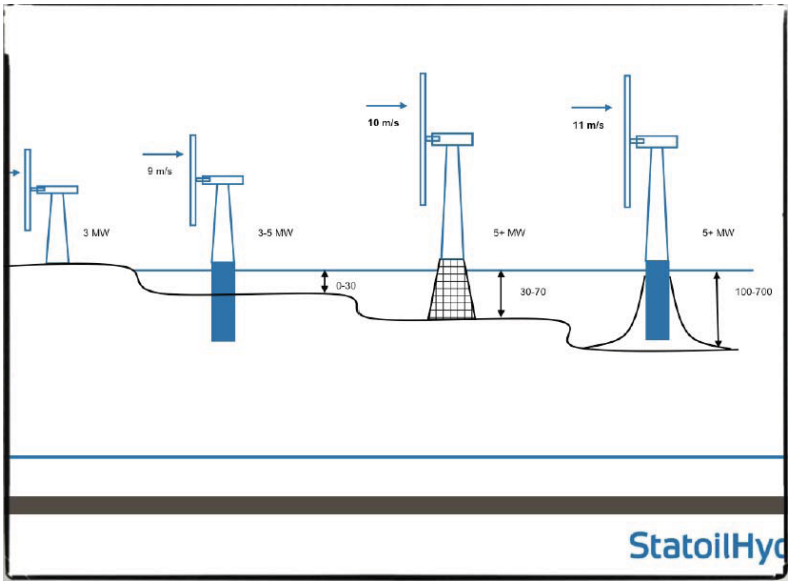

Figure 2. Offshore wind turbine foundation technologies. Developing technology research means that water depths suggested for each support structure in this image are not, we feel, reflecting current practice. In this study, we use water depth ranges and refined technology categories found in Table 1. Image courtesy of StatoilHydro.

In order to determine which depths correspond to which foundation technology, we consulted a database of existing projects in Europe called Wind Service Holland, which provides data, including foundation technology and water depth, for all operational offshore projects in Europe[3]. In addition, we used personal judgment to determine the water depths of future technologies based on our knowledge of the industry, personal communications with experts in the field of offshore foundation technology, and our experience on the American Wind Energy Association (AWEA) Offshore Wind Working Group's research and development committee, which one of the co-authors of this report (Kempton) chairs. The resulting water depth and foundation technology categories are shown in Table 1.

Table 1. Wind turbine foundation technology corresponding to water depth

Foundation Technology	Range of Water Depth (meters)
Monopile	0 – 35
Jacket	35 – 50
Advanced Jacket	50 – 100
Floating	100 – 1,000

[3] Wind Service Holland's offshore wind database of existing and planned projects can be located on the Web at http://home.kpn.nl/windsh/offshore.html

Combining both Maryland's bathymetry and the foundation/water depth categories in Table 1, the resulting offshore areas were mapped and are shown in Figure 3.

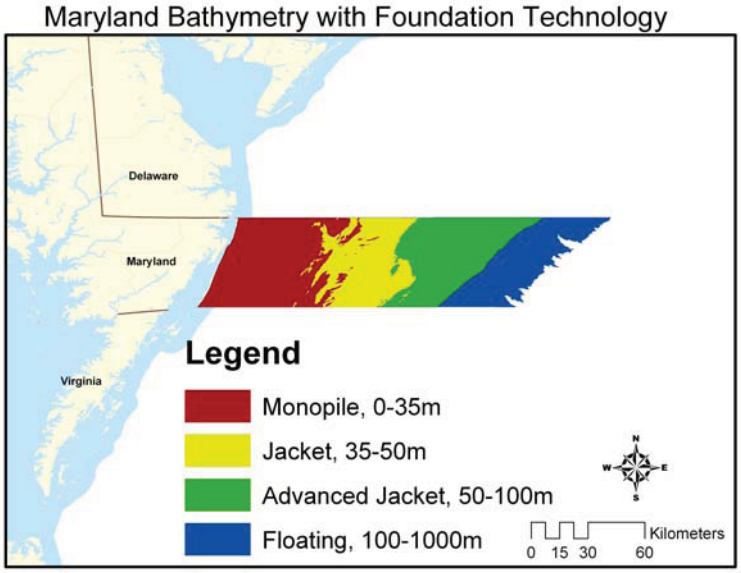

Figure 3. Areas of water depth that correspond to different offshore wind turbine foundation technologies.

1.2 Mapping Marine Exclusion Zones Using Nautical Charts

Marine exclusion zones can be identified using NOAA nautical charts. When imported into the ArcGIS family of Geographical Information Systems (GIS) software figures (known as shapefiles) can be created to better understand the exclusion environment in the area under study. NOAA nautical charts are available online from the Office of Coast Survey at: www.nauticalcharts.noaa.gov/mcd/OnLineViewer.html. The process for properly importing these charts and georeferencing them with the state or region under study is detailed in Appendix A. Using ArcCatalog to create shapefiles and ArcMap to edit those shapefiles, and by zooming in on the charts, users can trace features in the study area that may influence where offshore wind project development occurs. Common exclusion zones found on nautical charts include artificial reef habitats, dumping zones, designated military activity areas, designated shipping lanes, and marine sanctuaries. Figure 4 shows a nautical chart ranging from Cape May, NJ to Cape Hatteras, NC that was imported into ArcMap for identifying potential exclusion zones within the Maryland study area.

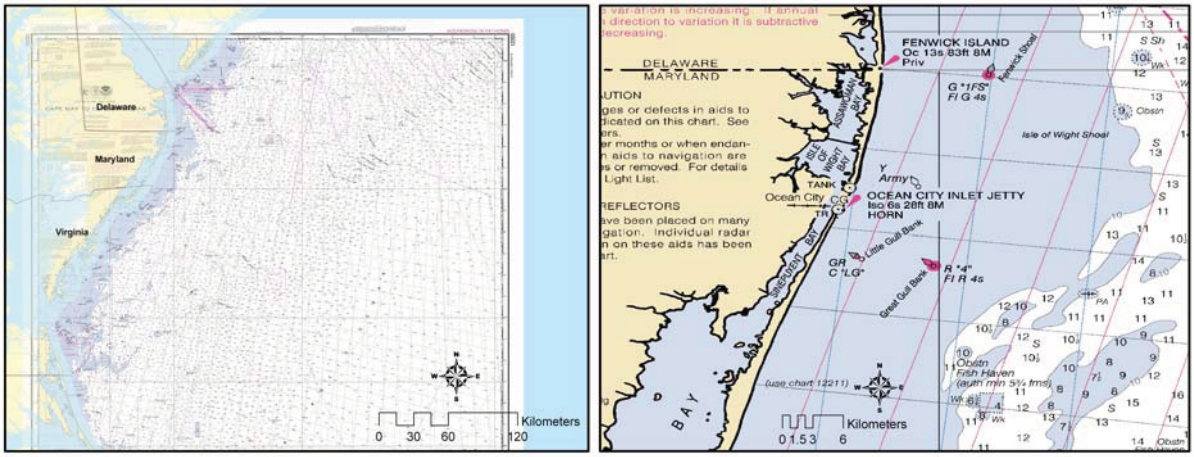

Figure 4. Georeferenced NOAA nautical chart covering Cape May to Cape Hatteras. Zoom out view (left) and zoom in view (right)

With no designated shipping lanes or military activity zones[4], the exclusion areas in Maryland's offshore waters are small. Within the Maryland study area, nautical charts show artificial reefs, labeled as 'Fish Havens', as the only necessary exclusion. Fish Havens are artificial structures placed on the seabed for the purpose of providing habitat to fish and other marine organisms. These structures are often pieces of infrastructure that need to be disposed of, such as old rail cars or large pieces of concrete from demolition projects (Gary 2009). A municipal dump site exists within the Maryland study area, but upon further investigation, it appears that the dump site is no longer in use. While geotechnical surveying may reveal that the site's seabed characteristics are not suitable for wind turbine foundation installation, we did not exclude this area from being developed due to the lack of use conflict. An area containing explosives was also designated as an exclusion zone in Figure 5, however the area falls outside of the study area and is therefore not included in the estimate of total area available for development. The next section describes other potential exclusion zones and use conflict areas within the study area.

[4] See sections 1.4 and 1.5 for a discussion of potential conflicts between offshore wind power development and areas that are or might be used by commercial shipping and military interests irrespective of the fact that they are not designated for such use.

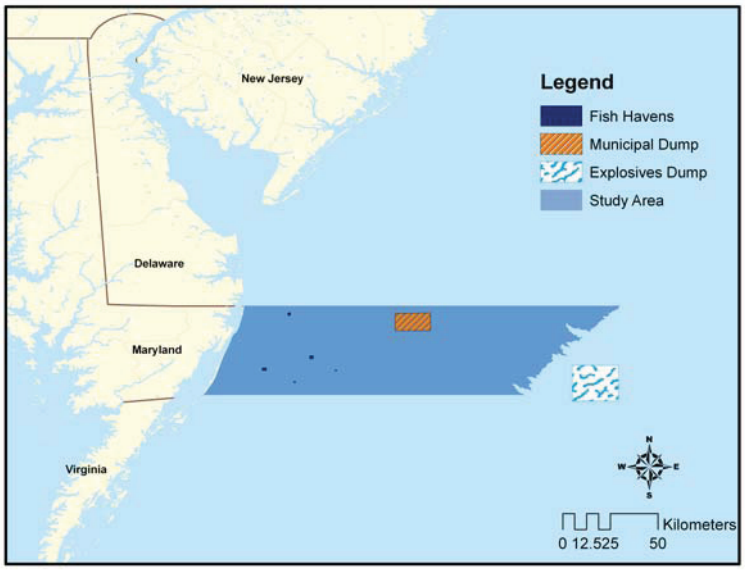

Figure 5. Marine exclusion zones mapped from NOAA nautical charts

1.3 Avian and Visual Exclusions

Nautical hazards are not the only important factors to consider when estimating viable offshore wind development area. The environmental impacts of any offshore wind project need to be studied in detail both before construction and during operation. Potential impacts include avian mortality or behavioral disturbance, marine mammal impacts, sensitive fish habitat disturbance, impacts on endangered species (AWI v. Beach Ridge Energy, Case No. RWT 09cv1519, D. MD Dec. 8, 2009), and others. The scope of this study is such that only potential avian impacts are addressed. In consultation with world renowned avian expert Paul Kerlinger, principal of Curry & Kerlinger LLC, it was determined that Maryland's coastline is part of the Atlantic flyway, a route taken by migratory birds flying north and south. Based on his experience, Dr. Kerlinger advised an exclusion zone one nautical mile wide parallel to the coastline because migratory birds tend to follow the coastline (Kerlinger 2009).

The aesthetics of offshore wind development are important. Visual impacts can motivate opposition (e.g. Cape Wind Project) and can potentially cause tourism revenue losses if people choose to go to a beach where turbines are less intrusive or not visible at all. Therefore, it is very important to fully understand the potential costs, or benefits, of placing wind turbines at different distances from shore. The University of Delaware's Center for Carbon-free Power Integration conducted a public opinion survey of Delaware residents to better understand the economic value associated with the placement of wind turbines at different distances from shore. This value, or willingness-to-pay, represents the amount of money a person would be willing to spend annually in perpetuity to move wind turbines each incremental mile further offshore. Survey respondents were given visualizations of what turbines would look like at different distances. The results of the study show that residents bordering the ocean (who live on average 0.6 miles from the coast) are willing to pay more to move turbines further offshore than residents adjacent to

the Delaware Bay or residents of Delaware (approximately 95% of the state population, hereinafter, "inland residents") (Krueger, Firestone, and Parsons, n.d.). In the case of ocean residents, once turbines reach 9 miles (that is, approximately 8 nautical miles) offshore, their willingness to pay to continue moving the turbines further is relatively small. For example, the difference in the marginal willingness to pay for ocean residents to move turbines from 6 to 7 miles offshore was approximately $10.00/month for 3 years. However, the difference in their marginal willingness to pay to move turbines each incremental mile further from shore beyond 9 miles is just $2/month/mile. (Ibid, Figure 3). In sum, the study found that ocean residents are willing to pay more than any other citizen to move turbine offshore, but once turbines are 9 miles (8 nautical miles offshore), the value in continuing to move them offshore is much less (Ibid.; See also, Krueger, 2007; Firestone, Kempton and Krueger, 2007).[5]

A study of opinions regarding wind turbine placement of out-of-state beach tourists at Delaware beaches and boardwalks, found that at 22 km (12 nautical miles), 94% would continue going to the same beach, 4% would go to a different beach in Delaware, and 2% would go to another beach (Blaydes Lilley, Firestone, and Kempton, 2010). At 5 nautical miles, 74% would remain at the same beach, 19% would switch to a different Delaware beach, with 7% going out-of-state. At one nautical mile, much greater beach switching behavior was observed, with 35% going to a different Delaware beach and 10% going out-of-state. On the other hand, at 5 nautical miles, they found that the likelihood of visiting a new or different beach at least once to view an offshore wind project was greater than stated avoidance and that 44% indicated that they would be likely to take a boat tour of the wind turbine project (ibid).

In light of these findings, and to be conservative, we applied an 8-nautical mile exclusion zone, in the shape of a semi-circle, around the tourism destination of Ocean City, MD. Additionally, an 8 nautical mile exclusion zone was drawn around Assateague Island National Seashore, as this is also a prime tourism location and may hold special place attachment for visitors (Firestone, Kempton and Krueger, 2009).[6] The overlap of these two semi-circles was so great that the decision was made to simply apply an 8-nautical mile exclusion zone from any point on the Maryland shoreline. Both the avian exclusion and the

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[5] It should be noted that coastal residents strongly prefer offshore wind turbines to new fossil fuel development even at close distances. Indeed, wind turbines have to be located at distances of less than one nautical mile from shore before those residents would prefer new fossil fuel development (Firestone, Kempton and Krueger, 2007).

[6] Although these near shore areas have been excluded in this report in order to provide a conservative estimate of Maryland's offshore wind resource size, in light of the finding noted in the previous footnote regarding coastal residents preference for offshore wind over new fossil fuel development, and given the fact that Maryland has greater control over development within state waters—the first three nautical miles from shore—and would obtain all the revenues should it choose to lease that area and that Maryland would share revenues with the federal government for wind projects that have at least one turbine within six nautical miles of its shore, Maryland may wish to consider nearer-shore offshore wind power development. See (see Federal Register, Vol. 74, No. 81, pp. 19638-19871 (April 29, 200), to be codified in pertinent part in the Code of Federal Regulations (CFR) at Vol. 30, Sections 385.540-385.543).

visual exclusion can be seen in Figure 6. In addition to the marine exclusion zones in Figure 6, a line labeled as "8g" is shown. This line is 6-nautical miles from the mean low water mark and represents the boundary for revenue sharing between states and the federal government of royalties paid by private developers for the use of public lands. The "8g" line was established by the Energy Policy Act of 2005 and gets its name from the subsection it amended contained in the Outer Continental Shelf Lands Act.

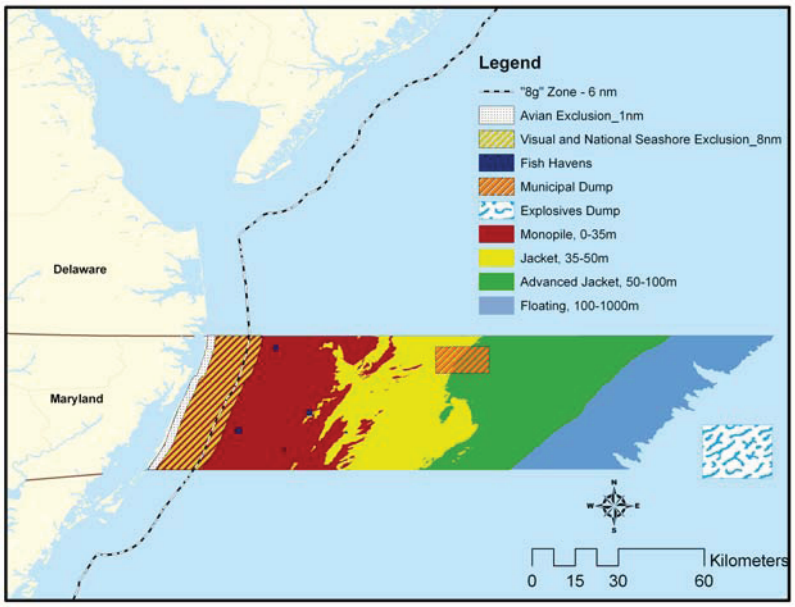

Figure 6. All exclusion zones for the Maryland study area

1.4 Potential Shipping Conflict Areas

As noted previously, there are no designated shipping lanes in Maryland's coastal waters. Thus, constructing zones to accommodate commercial shipping is a less precise process. The designated shipping lane entering the Delaware Bay ends at Maryland-Delaware border as it is extended east (this line also represents the northern border of the study area). Ship traffic leaving the Delaware Bay shipping lane is therefore free to disperse at random once in the study area. Commercial vessels do not randomly disperse, but rather tend to follow the shortest route between their port of departure and their port of arrival, accounting for bathymetric concerns and other navigational hazards. These principal routes, while not governed by maritime law, can be considered areas of conflicting use, and areas in which the U.S. Coast Guard and the Army Corps of Engineers (which must issue a permit to any such project under the Rivers and Harbors Act) are likely to raise concerns.

In order to understand where ships travel within the Maryland study area and where conflict appears to be most prevalent, we utilized the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). ICOADS is a data set of global marine surface conditions collected and reported by a fleet of about 4,000 ships known as the Voluntary

Observing Ships (VOS) (Corbett, Wang, Firestone 2006). An improved ICOADS data set, available from the University of Delaware and Dr. James Corbett[7], was imported into ArcMap to identify areas of high traffic within the study area. The data set improves on the raw ICOADS data set by eliminating outlying data points (Corbett 2010). Totals are represented within a 4 km by 4 km grid, or 16 square km. Resolution becomes a factor when zooming in as closely as the Maryland study area on this global dataset. As can be seen in Figure 7, clear economic shipping lanes emerge when zoomed out on the Atlantic ocean, while focusing on the Maryland study area reveals a less-clear picture of customary, habitual traffic patterns.

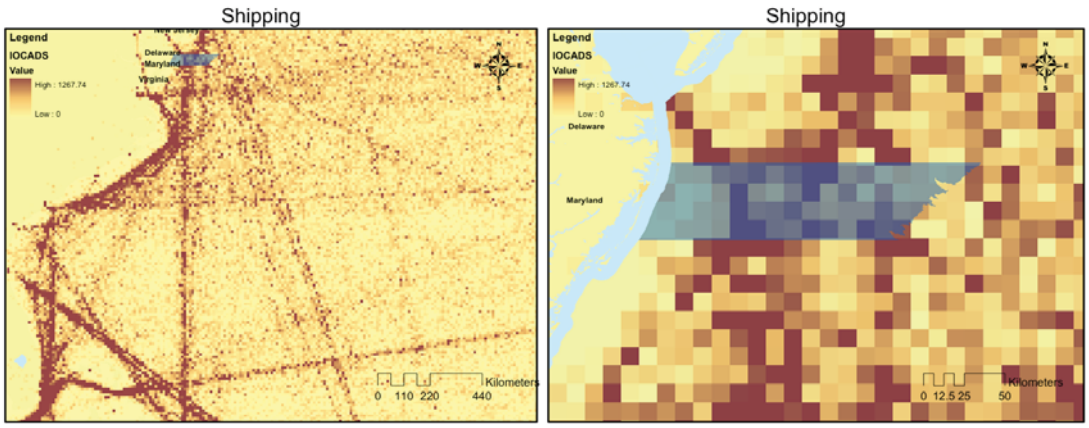

Figure 7. A view of the ICOADS data set for shipping, weighted by vessel power (Corbett, 2010). On the left, a view of the economic shipping lanes in the Atlantic from Florida to New Jersey. On the right, a less-defined picture of where ships are traveling in Maryland waters.

While it is hard to exactly define the routes ships are traveling through the Maryland study area, it was determined that an estimated 'potential conflict ' areas could be identified and outlined. Figure 8 shows the outlined potential conflict areas based on the ICOADS data above (Figure 7, right).

[7] See http://coast.CEOE.udel.edu/NorthAmericanSTEEM/

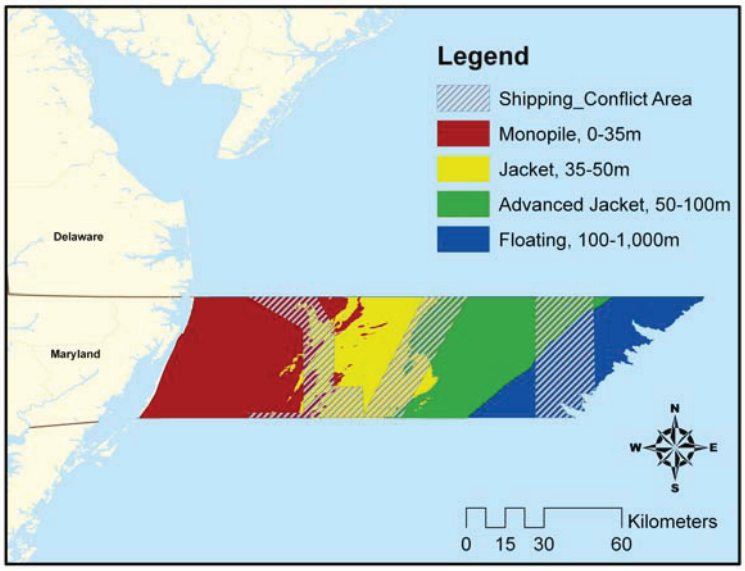

Figure 8. Potential shipping conflict areas within the Maryland study area

1.5 Potential Military Conflict Areas

According to a November 20, 2009 article, "representatives of the U.S. Navy command and the state's naval community shared their concerns [about offshore wind turbines] in Baltimore with officials of the Maryland Energy Administration, the Department of Business and Economic Development and other entities" (Brody 2009). The article quotes Todd Morgan, president of the Southern Maryland Navy Alliance, saying that the concern is over wind turbines producing artificial images that could disrupt military activity. According to the author, the Patuxent River Naval Air Station in St. Mary's County, Wallops Island on Virginia's Eastern Shore, and the Oceana Naval Air Station in the Hampton Roads region all use the open area over the ocean for military activities.

The interaction between military radar and wind turbines is a use conflict that needs greater examination and better understanding by all parties involved: military, state and federal government, and developer. Exactly which areas, if any, would need to be excluded is unknown at this time.

Section 2. Calculating Maryland's Offshore Wind Power Potential

2.1 Wind Resource Assessment

NOAA maintains meteorological buoys throughout the United States' Exclusive Economic Zone (3-200nm) that record information about marine conditions including water and air temperature, wind speed and direction, and wave height. The hourly interval data is available to the public on the NOAA National Data Buoy Center website. The records

for many buoys extend twenty years; however there are gap periods without readings when the instrumentation malfunctioned. To ensure accurate results when working with multiple buoys it is necessary to coordinate years when the data is available across all buoys. Unfortunately, NOAA does not operate any meteorological buoys within the study area. There is one meteorological station located at the Ocean City inlet, but it was installed in 2008 and therefore has only one year's worth of data. The closest buoy to the study area is Buoy 44009, located 12 nautical miles off the coast of Delaware. The original plan for this study was to extrapolate the wind profile from eleven years (1995-96, 1999-2005, 2007-2008) based on data availability at three different buoys: Buoy 44009, the offshore platform CHLV2, and Buoy 40014. The location of these weather stations ranges from 10 nm to 50 nm offshore and is shown in Figure 9. For reasons detailed below, only Buoy 44009 was used in this study.

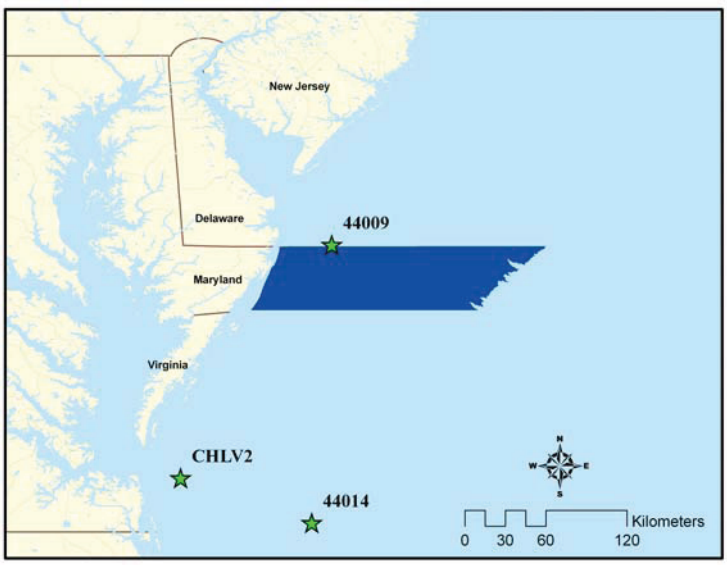

Figure 9. Location of three NOAA weather stations within closes proximity to the Maryland study area. Only wind data from Buoy 44009 was used in this study.

The data were stored in Excel spreadsheets and then imported into a matrix containing date, time, wind speed, and wind direction using MATLAB R2006b. The wind speeds were extrapolated to the hub height of a REpower 5M[8] wind turbine, a 5 megawatt (MW) machine with a 90-meter hub height, using the log law:

$$\frac{U(z)}{U(z_r)} = \frac{\ln\left(\frac{z}{z_o}\right)}{\ln\left(\frac{z_r}{z_o}\right)} \qquad (1)$$

[8] We use a 5MW wind turbine for calculations as the industry is moving toward larger turbines as they will deliver cheaper electricity per kilowatt-hour (kWh) than the current industry workhorses, which are in the 3MW range. Because 3MW wind turbines have shorter blades, they can be placed closer together than 5MW wind turbines, resulting in similar power production per square kilometer. As a result, from a power production standpoint, our choice is without significant consequence.

For Equation 1, $U(z_r)$ is the recorded wind speed, z is hub height, z_r denotes the anemometer height taken from the NOAA buoy website, and z_0 is the surface roughness. A surface roughness value of z_0 = 0.35 mm was used for the study. This value is a compromise between the z_0 values for calm sea and blown sea (Manwell, McGowan, and Rogers, 2002).

A visual analysis of average wind speed by month indicates that the wind profiles recorded at the three buoys are similar, as shown in Figure 10. A t-test confirms that the three different wind distributions constructed from eleven years data do not vary statistically ($p<.05$).

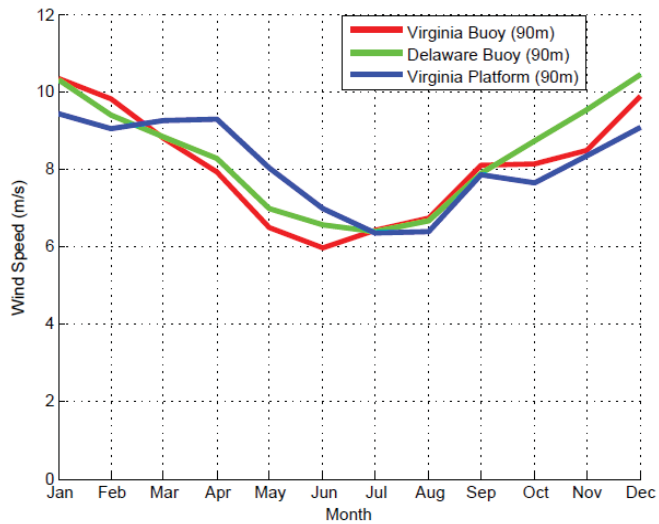

Figure 10. Eleven year monthly average wind speeds at 90 m hub height for the three meteorological stations considered for this study

Because the distributions do not vary significantly, and the offshore platform CHLV2 and Buoy 40014 are somewhat remote from the study area, the decision was made to use data from only the closest buoy, Buoy 44009. The hub height wind speed distribution from Buoy 44009 is presented in Figure 11. The eleven-year average wind speed at hub height of Buoy 44009 is 8.31 meters per second (m/s) with a standard deviation of 4.4m/s.

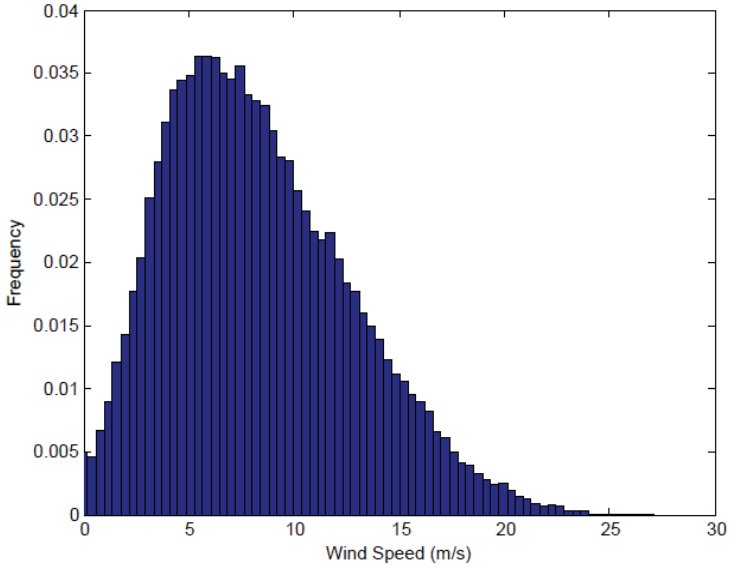

Figure 11. Hub height wind speed distribution recoded at Buoy 44009 over eleven years. The bin sizes are 0.4m/s.

2.2 Calculating Wind Power

The next step was to estimate the amount of power generated by a single turbine in a year. First, the power curve (Figure 12) for the REpower 5M turbine was approximated as a matrix containing wind speeds, in increments of 0.05m/s, and the corresponding power output for each increment obtained. For wind speeds in the range of 0 to 3.5 m/s (the cut-in speed)[9], the power output is 0 kilowatts (kW). For wind speeds between 3.5 and 13.5m/s (the lowest speed at which the turbine generates maximum power), the shape of the power output curve is estimated as a 7th order polynomial. Power output for wind speeds between 13.5m/s and the cut-out speed of 30m/s is 5000 kW. At wind speeds of greater than 30m/s, the power output is 0 kW, as the wind turbine shuts down to protect the gearbox and other turbine components from excessive wear or failure.

[9] The cut-in speed is the minimum wind speed required for the wind turbine to begin generating power. The REpower 5M machine has a cut-in wind speed of 3.5m/s.

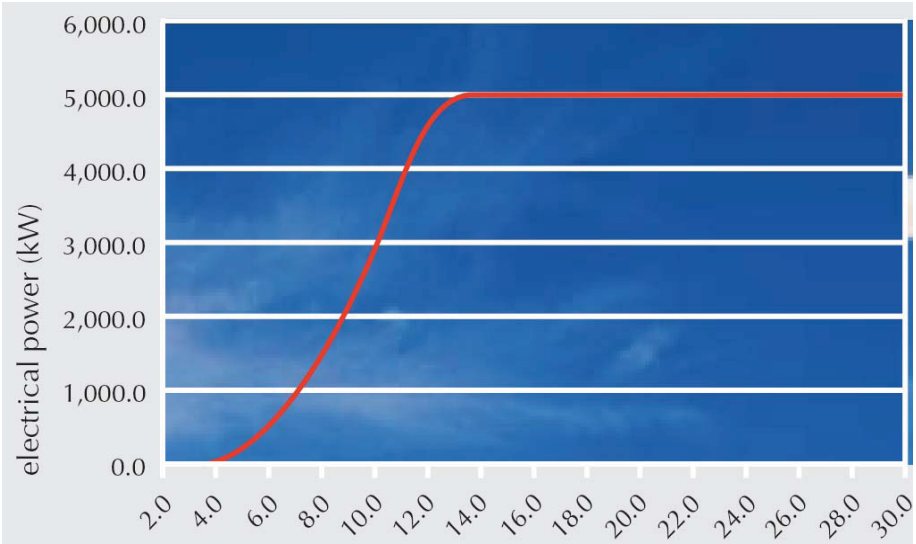

Figure 12. Power output curve of the REpower 5M turbine where the y-axis is power output in kW and the x-axis is wind speed in meter per second. Image Credit: REpower

Wind speed data from Buoy 44009 were then converted to power using the segmented power curve. Buoy wind speed-readings take place every hour and thus the power values are assumed to be constant for the entire hour, yielding kilowatt-hour (kWh) power generation values. The capacity factor was calculated from the equation below:

$$Capacity\ Factor = \frac{Average\ Power\ Output\ (kW)}{Maximum\ Turbine\ Output\ (5000\ kW)} \qquad (2)$$

The capacity factor for Buoy 44009 and the REpower 5M turbine is 0.3984, meaning the average power output of the REpower 5M is 1,992 kW. Monthly average power outputs were derived and a plot was created. A power distribution curve, a visual representation of the capacity factor, was plotted to present the frequency of wind speeds and the corresponding power outputs over the eleven year data range (Figure 13).

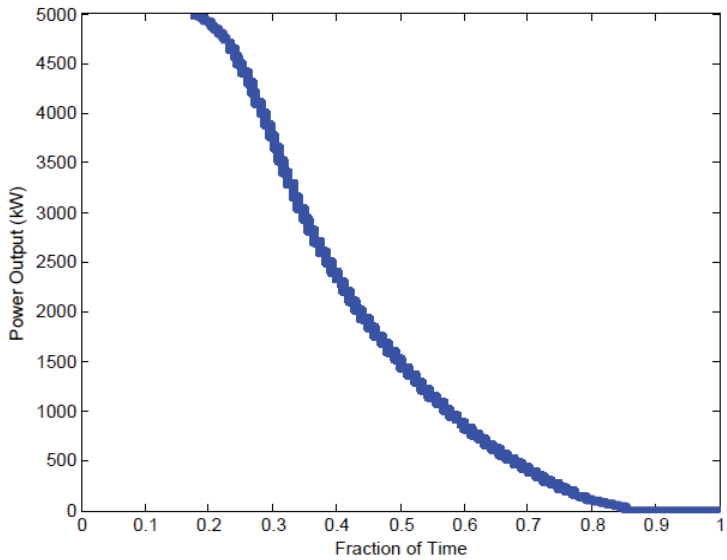

Figure 13. Power Density Curve of a single turbine at buoy 44009. The x-axis corresponds to the cumulative fraction of the total time that the power output (plotted on the y-axis) occurs over eleven years worth of data.

In order to determine the required spacing and layout orientation between turbines to ensure optimum power generation at a given location, it is necessary to analyze the prevailing wind direction. In addition to wind speed, the meteorological buoy data contains readings from an anemometer about the direction of the wind. Thus, it is possible to separate data points into bins according to the direction of the wind. The polar coordinates of the wind direction (where 90° represents North, etc.) are divided into 60 bins in 5 degree intervals. The analysis of prevailing wind direction can be performed in a number of ways.

- The total number of data points within a bin can be compiled. This represents the amount of time that the wind blows from any given direction in an average year (the "frequency").
- Average wind speed for each bin can be calculated and then plotted. From this, the direction with the highest average wind speeds can be determined.
- The average power output can be plotted. To find the average directional power output, the power output of each direction bin is averaged and plotted. This illustrates the directional winds that generate the most power.

Seasonal rose plots, sorted by wind direction including wind frequency, average wind speed, and average power output, were created and are shown in Figure 14. The plots are normalized by the maximum directional values: winter for average power and wind speed, and summer for frequency.

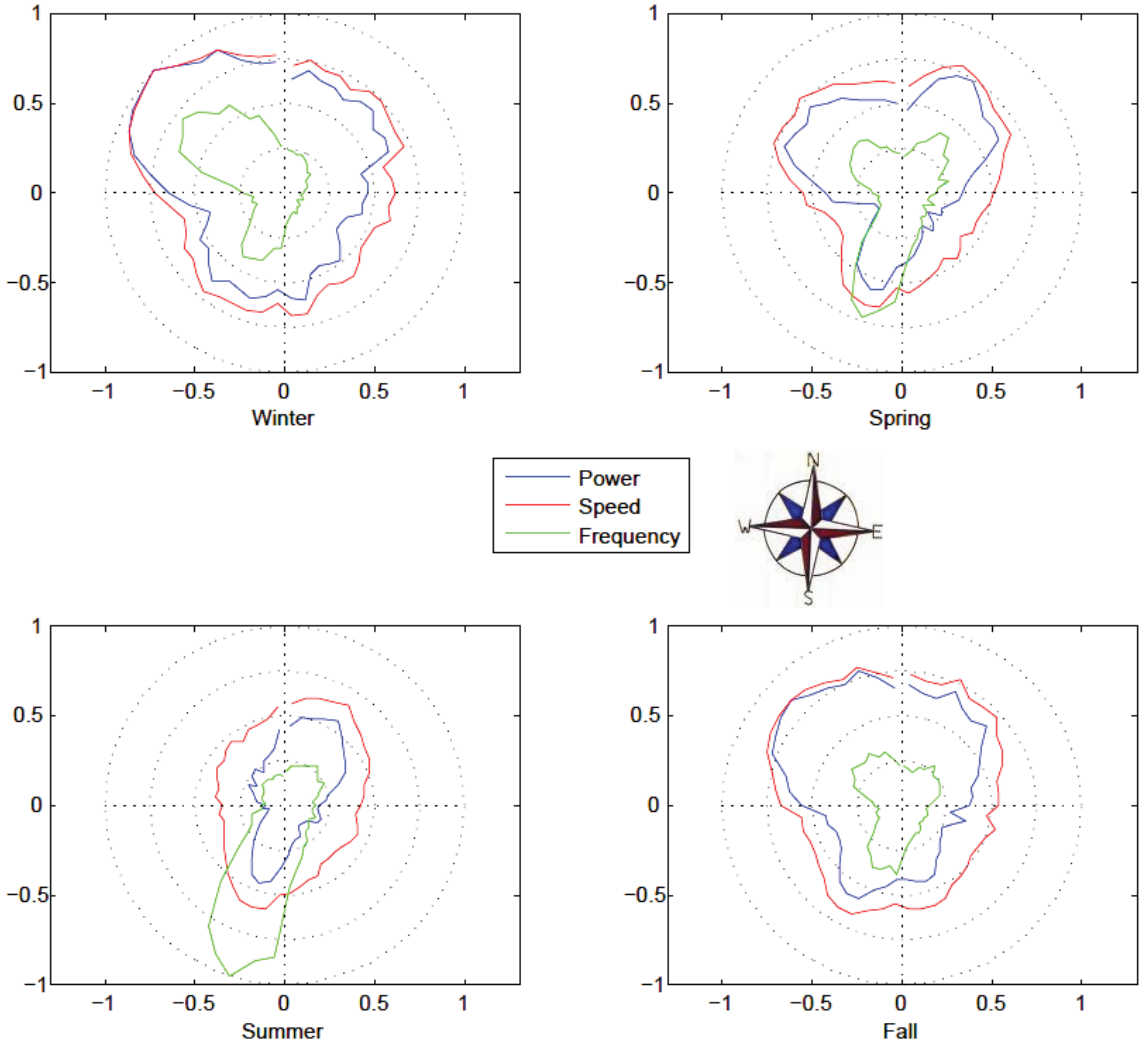

Figure 14. Seasonal Rose Plots depicting power, hub height wind speed, and wind frequency by direction. The values are normalized by the maximum yearly values.

The most power is generated during the winter season (December, January, February), followed by autumn (September, October, November), spring (March, April, May), and summer (June, July, August). The prevailing wind direction for Buoy 44009 is from the Northwest, especially during the winter months. During the summer months, most of the wind comes from the Southwest. Because demand for electricity is greatest in the summer, and electricity prices are the highest on the spot markets, it may be worthwhile for developers to consider siting the turbines in order to preferentially align the wind turbines to take advantage of summer winds. However, for this study, the decision was made to optimize power generation. To do this, turbines are positioned in closely packed rows, each turbine five rotor diameters apart crosswind and ten rotor diameters apart downwind. The turbines are aligned southwest - northeast, essentially in rows parallel to the shore, in order to maximize total power output (Figure 15).

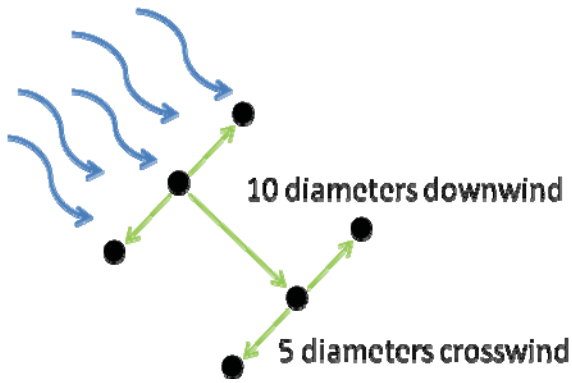

Figure 15. Diagram of the inter-turbine spacing used for this study, as well as direction of the rows.

The spacing factor is then calculated as follows:

$$Spacing\ Factor = (Rotor\ Diameter)^2 \times Downwind\ Spacing\ Factor \times Crosswind\ Spacing\ Factor \quad (2)$$

The rotor diameter of a REpower 5M turbine is 126m and the crosswind and downwind spacing factors are 5 & 10 rotor diameters respectively. Therefore, the spacing factor is 0.794 km^2.

2.3 Estimating Installed Capacity and Energy Production

The area that is available for offshore wind turbine installation is assumed to be the remaining area after removing the exclusion zones. The remaining area at each depth is presented in Table 2.

Table 2. The total area, exclusion area, and available area for each depth range.

Depth (m)	Total Area (km^2)	Exclusion Area (km^2)	Available Area (km^2)
0 – 35	3,470	1,148	2,322
35 – 50	2,311	1	2,310
50 – 100	2,723	0	2,723
100 – 1,000	2,171	0	2,171
Total	**10,675**	**1,149**	**9,526**

Using the spacing factor of the hexagonal spacing pattern, 0.794 square meters, the number of turbines that could be installed at each depth is calculated as shown in equation 4.

$$Number\ of\ Turbines = Available\ Area \times Spacing\ Factor \quad (4)$$

The nameplate wind capacity (i.e. total installed capacity) is found by multiplying the number of turbines by the nameplate capacity of a single turbine, which in this case is 5

MW. This value is of little practical use because wind turbines often do not operate at nameplate capacity. In order to compare offshore wind to traditional generation sources (i.e. Coal, Nuclear, Natural Gas), it is much more useful to use the unit 'average output' rather than installed nameplate capacity[10]. Average output is computed by multiplying the nameplate capacity by the capacity factor. The average output corresponds to the power generated on average over the course of the year. To determine how much energy (MWh) will be generated over the course of an average year, the average output is multiplied by the number of hours in a year - 8,760 hours. To generate a more accurate estimate of average power output and average annual energy production that can be expected, we derate the ideal output from an offshore wind project in Maryland by accounting for 'wake effect' and 'availability'. Wake effect refers to the loss of power due to increased turbulence caused by windward turbines in a large offshore project. Availability refers to the percentage of time that a wind project is able to generate electricity. It takes into account those times when there are planned and unplanned outages (e.g., scheduled maintenance, unplanned shutdowns, and extreme weather events). Consultation with leading experts in the field and recently published, peer reviewed research was used to establish availability and wake effect percentages. Here, we use a wake effect factor of 10% power loss (Barthelmie et al., 2007) and an availability factor of 95% (Musial, 2010).

Given the available area to place turbines, the wind analysis described above, and the de-rating factors for wake effect and project availability, Maryland has the potential to install almost 60,000 MW of offshore wind. This installation would have an average power output of 20,436 MW_a, generating over 179 million MWh of energy per year. Using existing, proven technology in shallow waters, there is potential to install 14,625 MW of capacity, generating 4,982 MW_a on average. Detailed results of this analysis are presented in Table 3.

Table 3. Power generation potential by depth.

Depth (m)	Available Area (km^2)	Wind Turbines	Nameplate Capacity (MW)	Average Output (MW_a)	Total Annual Generation (MWh/year)
0-35	2,322	2,925	14,625	4,982	43,642,320
35-50	2,310	2,910	14,550	4,956	43,414,560
50-100	2,723	3,430	17,150	5,842	51,175,920
100-1000	2,171	2,734	13,670	4,656	40,786,560
Total	**9,526**	**11,999**	**59,995**	**20,436**	**179,019,360**

[10] We use a capacity factor of .3984. Traditional generation sources (coal, gas, nuclear) have high availability and high capacity factors. Generally speaking, these generators have capacity factors in the .70 -.95 range. Thus, an offshore wind project with a 500 MW nameplate capacity would have an average output of approximately 200 MW; a coal plant with the same nameplate capacity would have an average output of approximately 370 MW (using the 2007 average capacity factor of coal plants of .74. The average capacity factor for nuclear in 2007 was .92 (EIA)).

For reference, the potential resource off Maryland's Atlantic coast can be compared with the state's current electricity demand. Maryland's total electricity sales in 2007 (65,390,600 MWh) were obtained from the Department of Energy's Energy Information Agency. The average load (7,465 MW_a) was calculated by dividing the total consumption by the number of hours in a year (EIA 2009).

Table 4. Offshore wind potential compared with electricity use in Maryland, 2007.

	Annual Generation (MWh/year)	Average Output (MW_a)	Percentage of Load
0-35m	43,642,320	4,982	67%
0-50m	87,056,880	9,938	133%
0-100m	138,232,800	15,780	211%
0-1000m	179,019,360	20,436	274%

These values illustrate the vast potential for wind power off of Maryland's Atlantic coast. For example, development within the 0-35m depth range, including a visual exclusion zone of 8 nautical miles from shore, allows the potential to site nearly 3,000 turbines, which on average could supply 67% of the Maryland electric load. Considering from 0 to 50m depth, offshore wind has the potential to fulfill 133% of Maryland's load. If fully developed out to 1000m depth, offshore wind power has the potential to generate over 179,000 Gigwatt-hours (GWh) per year. Compared to the state electric load of 65,391 GWh/year, the total offshore wind resource represents over two and half times the amount of electricity required to serve Maryland's electric load.

2.4 Available Resource Accounting for Shipping Conflict Area

The areas of heavy shipping activity within the study area span across the depth delineations, making it difficult to separate out conflict areas by depth. For this reason, the results of the shipping conflict areas are presented for the total study area. The total area in which conflict exists with commercial shipping is 3,300 km^2. Subtracting this value from the previous total area and then performing the calculations outlined above provides a conservative estimate of the total available area for offshore wind development. As shown in Tables 5 and 6, the total area available for offshore wind development, when taking into account commercial shipping conflict areas and the exclusions detailed in section one of this report, is 6,226 km^2. This area translates into average annual generation of 136,866 GWh/year.

Table 5. Power Generation after subtracting Shipping Conflict Areas.

	Available Area (km^2)	Wind Turbines	Nameplate Capacity (MW)	Average Output (MW_a)	Total Annual Generation (MWh/year)
Before Subtracting Shipping Conflict Areas	9,526	11,999	59,995	20,436	179,019,360
After Subtracting Shipping Conflict Areas	6,226	7,843	39,214	13,359	117,024,840

Table 6. Offshore wind potential after subtracting Shipping Conflict Areas compared with electricity use in Maryland, 2007.

	Total Annual Consumption/Generation (MWh/year)	Average Load/Output (MW_a)	Percentage of Load
Load	65,390,660	7,465	100%
0-1000m	179,019,360	20,436	274%
0-1000m subtracting Shipping Conflict Areas	117,024,840	13,359	179%

In sum, accounting for areas of heavy ship traffic reduces the available area for offshore wind projects by 35%, and therefore the total annual generation. Given the reduction in generation due to shipping, the available offshore wind resource still amounts to over one and half times Maryland's yearly energy consumption in 2007.

Section 3. Integrating Offshore Wind into Maryland's Energy Landscape

3.1 Demand for Renewable Energy in Maryland

Maryland's Renewables Portfolio Standard (RPS), enacted in 2004 and revised in 2007 and 2008, requires all utilities and competitive retail electricity providers in the state to source renewable energy for a portion of their electricity sales. This mandate generates significant demand for renewable energy in Maryland and within the Independent Systems Operator, PJM's, territory. Maryland's RPS designates three categories of renewable energy corresponding to different renewable resources, each with their own compliance schedule. Offshore wind energy would qualify as a Tier 1 resource[11]. The compliance

[11] Tier 1 resources include wind, qualifying biomass (excluding sawdust), methane from anaerobic decomposition of organic materials in a landfill or waste water treatment plant, geothermal, ocean energy

schedule for Tier 1 resources is shown in Table 5. Assuming load growth in Maryland increases at a rate of one percent (1%) per year, the number of Megawatt hours (MWh) needing to be generated by renewable resources in each compliance year is also shown in Table 5. Compliance with Maryland's RPS is achieved by obtaining eligible Renewable Energy Credits, or RECs. Each REC is equal to one (1) MWh.

Table 5. Maryland's RPS compliance schedule and associated REC obligations for Tier 1 resources, which includes wind power. Source: 2007 electricity sales data from EIA.

Year	Tier 1 (%)	Retail Electricity Sales (MWh), 1% growth per year	RECs Needed for Compliance
2007	1	65,390,660	653,907
2008	2	66,044,567	1,320,891
2009	2	66,705,012	1,334,100
2010	3	67,372,062	2,021,162
2011	4.69	68,045,783	3,375,071
2012	6.44	68,726,241	4,425,970
2013	8.1	69,413,503	5,622,494
2014	10.15	70,107,638	7,115,925
2015	10.25	70,808,715	7,257,893
2016	12.35	71,516,802	8,832,325
2017	12.55	72,231,970	9,065,112
2018	14.9	72,954,290	10,870,189
2019	16.2	73,683,832	11,936,781
2020	16.5	74,420,671	12,279,411
2021	16.85	75,164,877	12,665,282
2022	18	75,916,526	13,664,975

By forecasting the amount of RECs needed to meet the RPS obligation, the amount of wind energy or other Tier 1 resource needed to produce those RECs can be estimated based on two factors – the percentage of the total amount of RECs needed by 2022 that are produced from wind power projects and the capacity factor of the wind power turbines. Adjusting these two parameters based on trends in the market and the performance of wind turbines leads to different estimates of the amount of installed wind capacity needed for Maryland. Examples of various scenarios are shown in Table 6.

(including energy from waves, tides, currents and thermal differences), fuel cells powered by methane or biomass, hydroelectric plants less than 30 MW, and poultry-litter incineration facilities connected to the Maryland distribution system.

Table 6. Installed land-based and offshore wind capacity needed to meet the RPS obligation in year 2022, based on the percentage of RECs generated by wind power. In this table, land-based and offshore wind capacities were calculated with .35 and .40 capacity factors, respectively.

Percentage of 2022 REC obligation met with wind power	Land-based Installed Capacity Needed (MW)*	Offshore Installed Capacity Needed (MW)
25%; or 3,416,244 RECs	1,114	975
50%; or 6,832,488 RECs	2,228	1,950
75%; or 10,248,731 RECs	3,343	2,925
100%; or 13,664,975 RECs	4,457	3,900

3.2 The Cost of Offshore Wind Power and Electricity Prices in Maryland

Empirical cost data for offshore wind energy in the United States is scarce. And, as the initial contracts are signed, the conditions of each vary, as does the price agreed to between buyers and sellers.

The only competitively-bid contract for price is a 25-year power purchase agreement (PPA) signed between Delaware's largest electric utility, Delmarva Power and Light (hereafter "Delmarva"), and offshore wind developer Bluewater Wind. The Delmarva – Bluewater PPA provides insight into the price of offshore wind energy in the Mid-Atlantic region. Maryland's waters are close to the Bluewater Wind project and have many physical similarities, in wind regime and other marine conditions such as seabed morphology, bathymetry, waves, etc. Therefore, if the contract terms, project size, financing, and such were equal, the Delaware PPA might provide an estimate for the cost of offshore wind energy to Maryland that exists today. The long-term contracting of both energy sales and RECs is an important factor in obtaining financing for the large upfront cost of offshore wind development. The Delaware Bluewater Wind Project bid, which won out over a coal bid and a natural gas bid, suggests that large-scale offshore wind projects can be cost competitive with new fossil fuel generation after accounting for future fossil fuel prices and likely costs to emit carbon into the atmosphere.

The Delmarva – Bluewater Wind PPA expresses rates in 2007 dollars, and adjusts prices annually thereafter by 2.5%/year. In 2007 dollars, Delmarva will purchase energy from Bluewater at the BER of $98.93/MWh. Using the AIA of 2.5%, the 2010 price would be $106.54/MWh and the price in 2013, when Bluewater expects its project to be operational, will be $114.73/MWh—that is 11.4 cents/kWh.

* This assumes that 1000-4500 MW of capacity could be installed on land in Maryland. An analysis of the extent of Maryland land-based wind resources is beyond the scope of this report. The land-based wind turbine calculations are provided for comparison purposes only.

In addition to energy, the Delmarva – Bluewater PPA contracts for capacity associated with the wind project, amounting to a separate payment of $6.67/MWh in 2007 dollars. Delmarva also agreed to purchase RECs associated with the production of the wind energy at $15.32/REC in 2007 dollars. The 2010 price then would be $16.50/REC and the price in 2013, when Bluewater expects its project to be operational, will be $17.77/REC. Delaware's RPS Act provide a multiplier of 350% for each REC associated with the 200 MW to be sold to Delmarva, resulting in Bluewater obtaining 2.5 additional RECs for each MWh generated that is can sell on the market.

By contrast, recently a 20-year PPA was entered into between Deepwater Wind and National Grid for power produced by a small wind project in state waters off of Block Island, Rhode Island. The PPA price begins at $244/MWh (or equivalently 24.4 cents/kWh), increasing at 3.5% per year. This is well above market price on the mainland, but actually below the cost of electricity on the island itself. This cost is probably not representative of larger utility scale projects; however, the relatively high price is understandable given the small size of the project and the abnormally high electricity rates paid by Block Island residents. In sum, we do not feel that the Deepwater-National Grid contract provides a good source of price information for Maryland.

The Request for Proposals (RFP) for offshore wind in New Jersey acts as a good proxy for the capital cost of building an offshore wind project (NJBPU 2007). A comparison of capital costs for the three projects moving forward in New Jersey shows that they range from $3.1 million/KW to $4.3 million/KW. We cannot compare these costs directly to the Bluewater and Deepwater PPAs, which are expressed in cents/kWh. It is nonetheless worth noting that capital costs estimates vary considerably, with the low capital cost figure being 28% less than the high one—the implication being that prices are in flux.

Finally, the market price of electricity is determined locally at the point of interconnection. Thus, to compare the cost of offshore wind to market prices, the zonal price at the point of interconnection needs to be derived. PJM coordinates the transmission of wholesale electricity in Maryland. The PJM region is broken into seventeen zones as shown in Figure 16. Offshore wind projects off the coast of Maryland will be interconnected into the Delmarva Power and Light (DPL) zone. In 2008, the most recent year for which there is a complete annual market report for PJM, the zonal day-ahead, load-weighted, average Locational Marginal Pricing (LMP) for DPL was $84.24/MWh. This figure is up from 2007 when the same zonal average was $66.84/MWh – an increase of $17.40/MWh, or 26% over the 2007 price.

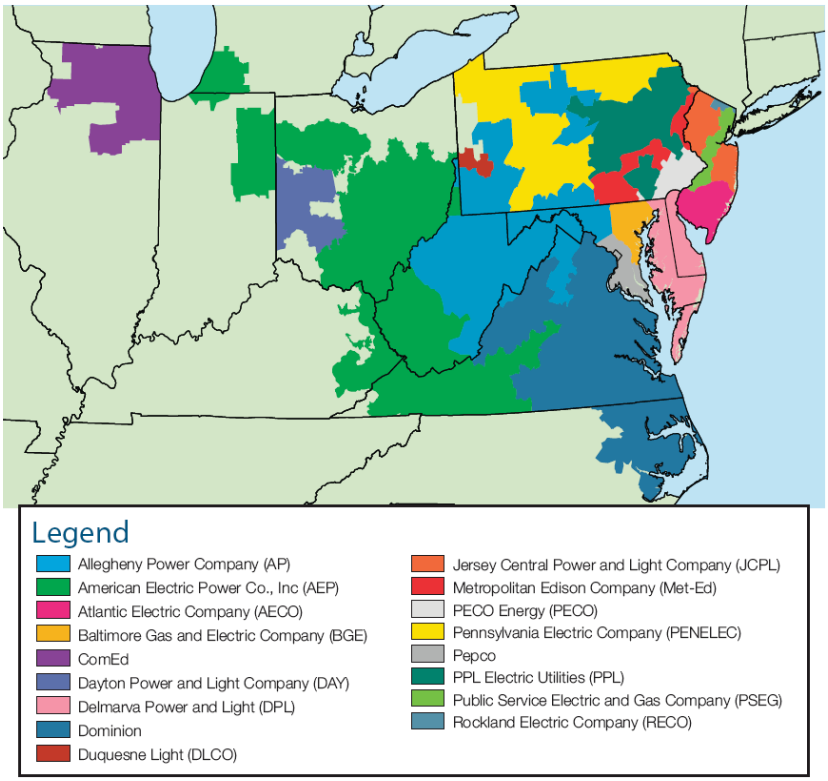

Figure 16. The PJM territory split into zones

Offshore wind is often compared with land-based wind and found to be more expensive. However, this comparison often lacks the context of zonal pricing in the PJM region. Generally speaking, zones in the western portion of the PJM territory have substantially lower LMP prices than do zones in the eastern portion. The LMP algorithm is a complicated one, but two important factors that drive the price differential between western and eastern zones are fuel type and transmission congestion. Even within the state of Maryland, there exists a substantial difference in LMP as one moves from the western most zone, Alleghany Power Company (AP), to the eastern zones of Baltimore Gas and Electric (BGE) and Pepco. This differential, both within Maryland and PJM as a whole, is relevant because most, if not all, land-based wind facilities will be built in the eastern portion of PJM. Therefore, price comparisons should not be made between land-based wind and offshore wind, but rather between wind energy and the zonal price where the resource is interconnected within the PJM system.

In comments submitted to the Delaware Public Service Commission (DEPSC), Dr. Jeremy Firestone, associate professor of marine policy at the University of Delaware, detailed this type of land-based vs. offshore wind price comparison. Using a land-based wind project planned for western Maryland[12] and the Bluewater Wind offshore wind

[12] The planned land-based wind facilities that Delmarva Power entered into a PPA with are Synergics' Roth Rock Wind Energy project (40 MW) and Synergics' Eastern Wind Energy project (60 MW). Both are located

project, Dr. Firestone analyzed the claim that land-based wind was much cheaper than offshore wind. According to an independent consultant hired by the DEPSC, the nodal price of the land-based wind project was, at the time, $43-44/MWh. The nodal price at the location where the Bluewater Wind project would interconnect was $70.33/MWh (IC Report 2008). Thus, all things being equal, the contract price of the land-based wind project would need to be $27/MWh cheaper than the Bluewater project to be of comparable value (Firestone 2008).

In sum, there is not enough information to say with certainty what the price of offshore wind will be. The Delaware project suggests that is it possible, if in a competitive situation, to design a project in that is within a few REC multiples[13] of being at competitive market price. This will be more certain when either the project is successfully built for that price, and/or we see the prices offered by other projects in the area of 300 MW or larger in size.

Conclusion

The results of this preliminary study indicate that Maryland's feasible wind resource off of its Atlantic coast (including both state and federal waters) is large enough to significantly contribute to the electric demand in the state. Using existing, proven technology (monopile; 5 MW turbines) and accounting for various social, environmental, and nautical exclusion zones and conflict areas, Maryland's available offshore wind resource could provide 67% of the state's electric load[14]. As deeper water technology becomes available, Maryland's offshore wind resource has the capability of providing 179% of the state's electric load. This resource thus represents an opportunity for Maryland to drastically reduce CO_2 emissions by the state's electric power sector and increase air quality in the region. The large amount of resource available is dependent on our assumed small number of zones excluded due to conflicting uses. Our calculated resource size would be reduced if the military or other organization is able to reserve areas for their exclusive use.

If we take the recent Power Purchase Agreement contract in Delaware as representative, the price of offshore wind power is only moderately higher than fossil fuel electricity. However, if the Deepwater-Rhode Island price is representative (we have argued it probably is not), then the price is over double the cost of market energy. Clearly the pricing issues need to be better understood. In any case, the price would be expected to

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in Garrett County, Maryland. The price for both 20-year PPAs is $81/MWh (for energy and RECs) in 2008 dollars.

[13] In Delaware, a state law amending the state's RPS, passed subsequent of the PPA signing between Delmarva and Bluewater, provides a 350% multiplier for RECs generated from offshore wind power.

[14] This 67% figure does not account for the amount of shipping conflict area in the 0-35 m depth range. However, Figure 8 shows that very little shipping conflict area exists in water less than 35m, and thus the 67% figure would not be reduced much by shipping.

drop sharply as the industry develops technically, and as it establishes supply chain and manufacturing in the region.

Offshore wind power also generates the RECs needed to meet Maryland's Renewable Portfolio Standard (RPS). The RPS mandates that 18% of Maryland's electricity is supplied by Tier 1 renewable energy sources, which includes wind energy, by the end 2022. To meet this goal entirely with offshore wind energy would require the installation of 3.900 MW, or an average of 300 MW per year. Using 5 MW machines, this would amount to the installation of sixty (60) turbines per year for thirteen years.

Building out Maryland's offshore wind potential would also benefit the state's economy for offshore construction, maintenance, supply chain, and/or turbine manufacturing. Each aspect represents a separate opportunity; including installation, operations and maintenance facilities, which need to be located in proximity to the project. Also, with manufacturing anywhere in the region, some sourcing of turbine components would likely be from Maryland's manufacturing sector. In contrast, buying fossil electricity from the market, delivered from distant fossil power plants, will not meet environmental goals and is unlikely to have any beneficial effect on the Maryland economy.

In sum, Maryland's offshore wind power potential appears to be very large, on a scale comparable to the entire state's need for electricity. Development of this resource appears to be the easiest and most cost-effective way to meet Maryland's renewable portfolio standard, increase its new electricity generation, and to modernize and diversify its economy.

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Appendix A: Georeferencing Nautical Charts in ArcMap Methods

1. Open web browser and connect to the URL above.
2. Under 'Select an Area to View', click on your region of interest (Atlantic Coast for this study).
3. A table appears with the following characteristics (example):

Number	Scale	Title
12200	419,706	Cape May to Cape Hatteras

4. Scroll down the table to a chart title of interest and click on the 'Number'.
5. A new window appears with the chart. In this window you are free to view the chart using the zoom and direction controls at the bottom of the map.
6. To import this chart into ArcMap, you must download the Raster Navigational Chart (RNC) from the link in the top right of the screen, 'Download RNC'.
7. A new window appears titled 'User Agreement'. Read the agreement and scroll to the bottom of the screen. Click the 'OK' link to begin download.
8. Click 'Save' when prompted.
9. The chart will download as a .zip file with the chart number as the file name, if you don't choose to change the name of the file. If you will download multiple charts, it is suggested to organize in an appropriate manner. For this project, the author created a folder 'NOAA Nautical Charts' and saved each chart as 'Chart Number_Chart Description'.
10. After the file has finished downloading, open its file location and right click on the zipped file.
11. Select 'Extract All…'
12. Follow instructions for the 'Extraction Wizard' by clicking 'Next', 'Next', 'Finish'.
13. Your file should now appear in the same folder as your zipped file.
14. Open ArcCatalog
15. Click on your chart file folder, click on the folder 'BSB_ROOT', click on the folder with your chart's number. You should now see a raster file labeled as 'Your chart's number.KAP'
16. Open ArcMap. Click and drag the raster file to the 'Layers' column.
17. A notice appears asking if you want to create pyramids. Select 'Yes'
18. Your new Raster Navigational Chart layer should appear

***Note – Your RNC will have the Spatial Reference 'GCS_WGS_1984'. For your chart layer to properly georeference with your land shapefile (state or otherwise), your shapefile must be in the same Spatial Reference. This Spatial Reference can be found in the folder 'Geographic Coordinate Systems', then in the folder 'World', then the file 'WGS 1984.prj'.**

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