Calculating the offshore wind power resource: Robust assessment methods applied to the U.S. Atlantic Coast

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ABSTRACT

This article describes improved techniques to calculate the wind power resource of an offshore area. The method uses publicly available oceanic, environmental and socio-economic data to identify areas less suitable for development due to physical or technical constraints, safety or other hazards, environmental concerns, or competing uses. Using wind speed data from meteorological buoys, annual energy output is calculated for a representative offshore wind turbine. The average power resource is determined by dividing the total available area by a wind regime and the turbine-specific effective turbine footprint, yielding the maximum number of turbines, and then derating the output to account for wake effects and operational availability.

These techniques are applied to quantify the previously undocumented offshore wind resource off the coast of Maryland, a U.S. Atlantic coastal state. We consider only the open-ocean Atlantic and not Maryland's substantial estuary, the Chesapeake Bay. We find that the wind field is fairly uniform, but exclusions of ocean areas due to competing use may be substantial, reducing the energy resource estimate significantly. Nevertheless, we find that even excluding these areas Maryland's offshore wind resource could supply an annual average of 14,087 Megawatts (MW$_a$), or 123,400 GWh of energy per year. This is equal to 189% of the state's annual electricity consumption. Further restricting to only shallower-water foundation technology (monopiles), average power output would still be 70% of electricity demand. We conclude with a discussion of policy options for coastal states.

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1. Introduction

This study refines a prior published method used to characterize offshore wind resources, and presents the findings in a way we believe to be most accessible to policy makers and the public. The offshore wind resource of the United States is substantial and represents a renewable source of power largely located near dense coastal populations with large and growing electric loads [1]. However, making decisions about development of the resource requires a greater understanding and more complete data than wind speeds. Additional information, such as average annual and seasonal power output, ocean use conflicts, environmental risk considerations, and integration with the electric grid are all required for an offshore wind power assessment that is useful for making policy decisions.

The land-based wind resource over the continental U.S. has been analyzed by a number of studies over the past several decades, starting in the 1970s [2–4]. Most recently, detailed state-by-state analysis of land-based wind speeds have been made available to the public [5]. These resource maps facilitate public and private interest in wind energy and can stimulate more expensive site-specific assessments, including direct wind measurement, environmental and other conditions, to make site development decisions. To date, only a small fraction of the land-based wind resource has become operating generation, nevertheless, at the time of writing the U.S. capacity of land-based wind power is the second largest in the world, with over 40 GW installed at the end of 2010 [6].

The offshore wind resource in the U.S. is less well understood or quantified. In many cases the size of the offshore wind resource is unknown by policy makers which leads to uninformed decision-making and may contribute to the slow adoption of offshore wind power in the United States. The U.S. has yet to install an offshore wind turbine and only a few offshore meteorological towers capable of measuring wind speeds at or near a wind turbine's hub height
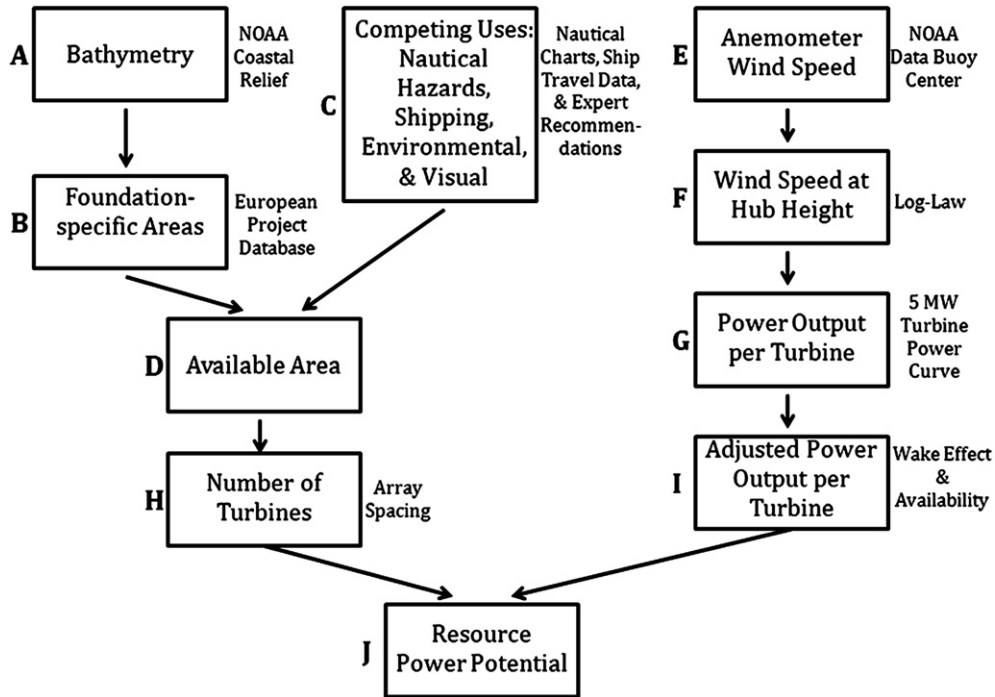
Fig. 1. Methodology developed for this study. The boxes refer to individual steps, and the labels to the right denote the databases or equations used.

have been deployed because they are more expensive and logistically challenging than installing onshore meteorological towers or ocean buoys. Thus, in lieu of offshore meteorological towers, some offshore wind resource studies extend land-based measurements to the areas over the ocean via modeling techniques [7,8]. Others have characterized the resource by using offshore wind measurements from buoys or satellites and extrapolating those measurements to wind turbine hub height [9–11]. Furthermore, data collection on competing uses, environmental habitats, and geologic conditions of the ocean is less complete than on land. In light of recent proposed offshore wind farms in the U.S., particularly in the Mid-Atlantic and Northeast regions, such efforts are ramping up both by state governments [12,13] and by independent academic studies [11].

In this paper, we refine general methods for offshore wind assessment, and then apply them to the ocean waters off Maryland's Atlantic Coast. The results provide an estimate of Maryland's feasible offshore wind energy resource, using a methodology that is accessible and reproducible. Since an initial unpublished draft of this work, the state and federal government have begun permitting processes for wind power development off of the Maryland coast: the US Department of the Interior, Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) designated a Wind Energy Area (WEA) off the Maryland coast [14] and Maryland Governor Martin O'Malley proposed legislation in 2011 to require utilities to enter into long-term contracts with offshore wind developers. Below are further comments on the BOEMRE (which in October 2011 became BOEM) effort. We hope that this study will encourage further scrutiny of the offshore wind power resource and its ability to provide renewable electricity for coastal regions.

2. Methods

The methodology developed for this study is displayed in Fig. 1. Each step of the method in Fig. 1 is described in one of the following sub-sections of this article. Each box refers to a step in the analysis; when a step requires data sources, they are listed outside the box, to the right.

2.1. Calculating the area suitable for offshore wind development

Certain offshore areas are very likely to be excluded from wind development, due to bathymetry, nautical hazards, potential freight shipping conflicts, and biological and visual impacts of wind turbines. Other exclusion factors may exist that are not addressed in this article. For example, Maryland is one of a handful of coastal U.S. states for which concerns have been expressed that offshore turbines could limit the effectiveness of radar, particularly military radar [15].

2.1.1. Bathymetry and turbine foundation technology

The water depth at any potential offshore wind development site is critical for determining the appropriate foundation technology at that location, which in turn is used to assess technological maturity and the cost of installation. In this study, we use three-arc second resolution, satellite bathymetric data made available by the U.S. National Oceanographic and Atmospheric Administration (NOAA) to delineate areas based on depth [16] (Fig. 1; Box A). Fig. 2a illustrates the bathymetry of the Delmarva region, a gently sloping continental shelf with very large shallow areas. This feature of the mid-Atlantic allows currently available, less expensive, shallow water offshore wind technology to be deployed over large areas in the short term, and deeper water technologies to be deployed as they are developed, tested, and become commercially available. (Light blue designates state waters, within 3 nm of shore. These waters are not considered further here in order to simplify analysis of exclusions, as the near-shore exclusion analysis is more data-intensive.)

The twelve bathymetric depths in Fig. 2a are next divided into four water depth ranges appropriate for today's primary offshore wind turbine foundation technologies. Shallow water technologies, used by the majority of installed projects in waters up to 35 m, are monopile and gravity foundations. At the next deeper range, jacket foundations, including tripods, quadrapods and lattice structures, have been deployed in waters as deep as 45 m.[1] The third range is

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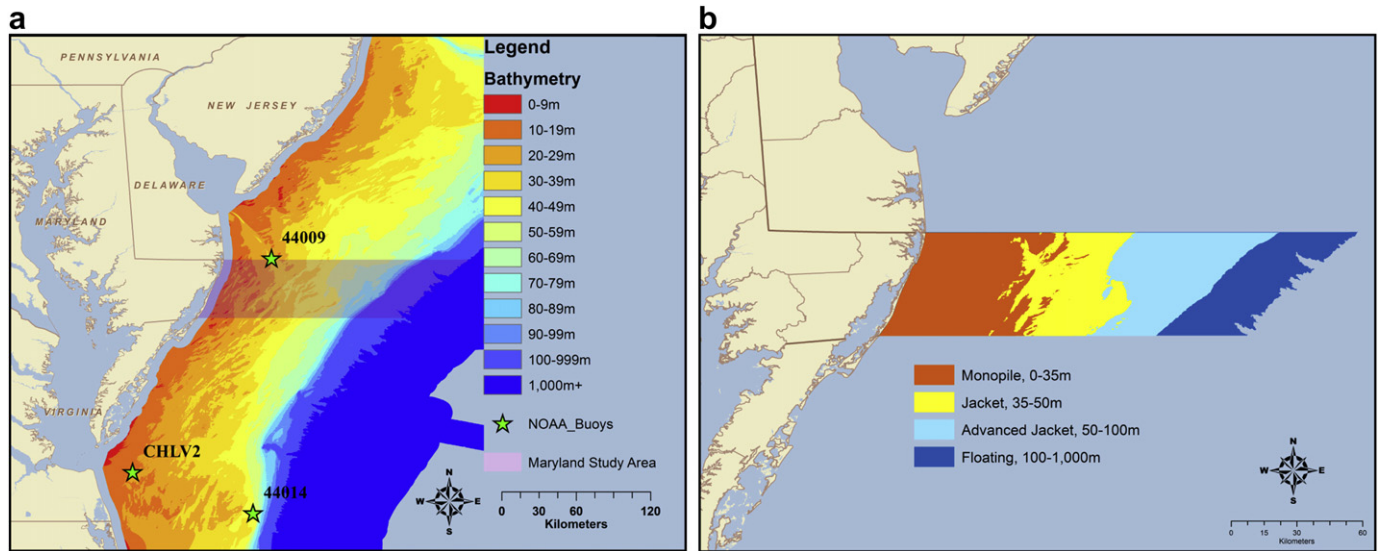[1] See Beatrice (Scotland), and Alpha Ventus and Bard (Germany) projects.

Fig. 2. Bathymetry and corresponding foundation technologies. On the left (a), Bathymetry of the Federal waters of the Atlantic outer continental shelf as well as the meteorological buoys used in this study shown in relation to the study area. Bathymetry is not shown for state waters, in bays and from shore to three (3) nautical miles into the Atlantic. On the right (b), Bathymetry corresponding to offshore wind turbine foundation technologies.

an extension of the previous, as jackets designs have been validated on paper to depths of 100 m [17]. Our fourth depth division is for still deeper waters, where we believe only floating turbines will be practical. These have not been commercially demonstrated either, although one utility-scale (2 MW) 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 m. Similarly, the University of Maine is planning a small-scale test of floating turbines at depths greater than 60 m.

Empirical data matching water depths to corresponding foundation technology was found in online database of existing offshore wind projects maintained by 4C Offshore Limited [18]. This mapping of turbine technologies to water depths is represented by Fig. 1; Box B. This database provides foundation technology and water depth for most operational and under construction projects in Europe. The data was collapsed into discrete water depth and foundation technology categories, shown in Table 1.

Combining the foundation/water depth categories in Table 1 with the bathymetry in Fig. 2a. We map the four technologically distinct depth ranges and resulting offshore wind power areas shown in Fig. 2b.

Fig. 2b shows the relative sizes of ocean area depths appropriate for each type of foundation technology. For example, the largest area is appropriate for monopile foundations, the foundation with which there is greatest experience and which is currently the least expensive. Floating platforms, if we accept the imprecise guideline that they are limited to depths up to 1 km, do not add much more power given Maryland's bathymetry. It should be noted that this is very different in other coastal states. Off California, for example, the sea floor drops quickly from shore, thus the areas appropriate for

monopile and jacket foundations are much smaller [19]. In such conditions floating technologies would be relatively more important. Establishing water depth limits of current offshore wind foundation technology is the first step in the method we are illustrating with this example of Maryland. This method draws from Dhanju et al. [11] and Kempton et al. [9], although we feel the depth intervals of Table 1 and Fig. 2b are a better match to the range of foundation technologies than are those of the cited prior work.

2.1.2. Exclusion of nautical hazards

Many marine zones with existing use can be identified using NOAA nautical charts [20]. Nautical charts commonly show artificial reef habitats, dumping zones, military activity areas and other danger zones, designated shipping lanes, and marine sanctuaries. These charts are for navigation, they do not claim to show what might or might not be excluded for marine construction, but may be used as a plausible guide.

Maryland, unlike its two neighboring states, Delaware and Virginia, has no designated shipping lanes. And unlike Virginia, it has no military activity zones indicated on NOAA nautical charts. Nautical charts show artificial reefs, labeled as 'fish havens', these are artificial structures, such as old rail cars or concrete pieces of demolished buildings placed on the seabed for the purpose of providing habitat to fish and other marine organisms. Wind turbine foundations, as hard structures, might improve the artificial reef habitat, but in this estimate we take the opposite approach and exclude these areas, as an illustration that some habitat areas may be excluded for marine protection reasons. Another nautical chart item is a municipal dump site, within the Maryland study area, no longer in use. We did not exclude this area from being developed because we find no evidence of use conflict.

2.1.3. Potential shipping exclusions

As previously noted, there are no designated shipping lanes in Maryland's coastal waters. Thus, identifying commercial shipping exclusions is a less precise process than when shipping lanes are designated. Ship traffic leaving the Delaware Bay exits the shipping lane in Delaware's offshore area prior to entering the waters off Maryland, and is therefore free to steer at any bearing once in the study area. Commercial vessels do not randomly disperse, but

Table 1
Offshore wind turbine foundation technologies matched to appropriate water depth ranges.

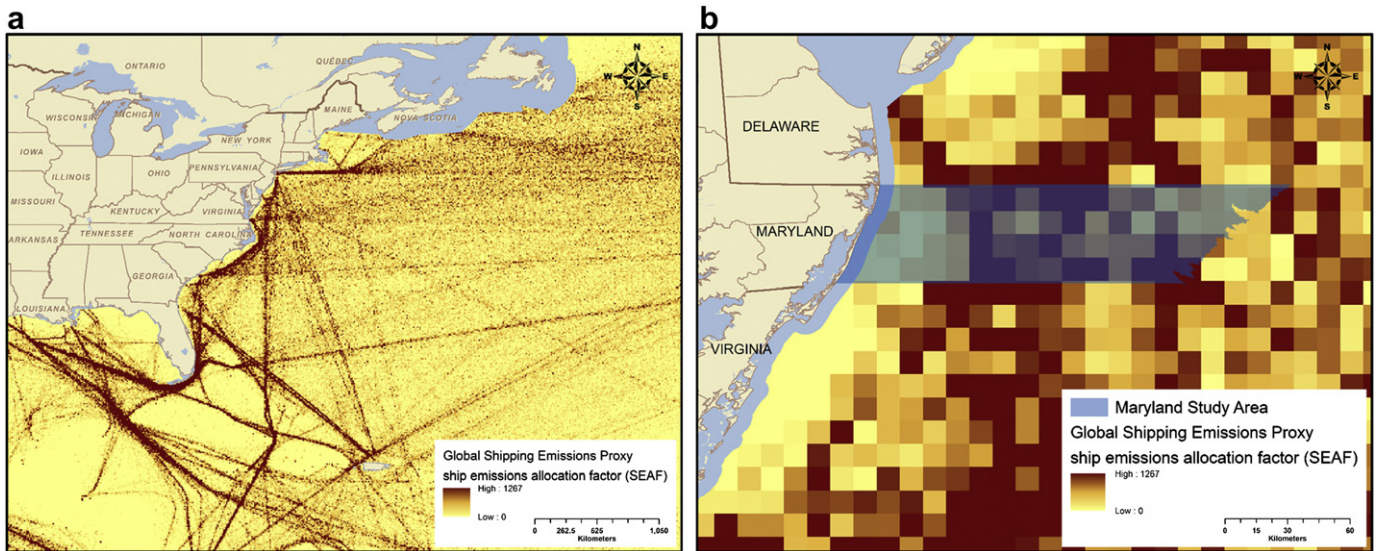| Foundation technology	Range of water depth (m)
Monopile	0–35
Jacket	35–50
Advanced Jacket	50–100
Floating	100–1000

Fig. 3. Global shipping emissions proxy data used to identify economic shipping lanes based on a ship emissions allocation factor (SEAF). On the left (a), a view of the economic shipping lanes in the Atlantic. On the right (b), a coarser view of ship proximity off the coast of Maryland.

rather tend to follow the shortest route between their port of departure and their port of arrival, accounting for navigational hazards. These principal routes, while not governed by maritime law, can be considered areas of conflicting use and areas in which concerns could be raised by the U.S. Coast Guard and the Army Corps of Engineers. The Corps must issue a permit to any such project under the Rivers and Harbors Act.

In order to understand where ships travel within the Maryland study area and where conflict appears to be most likely, we utilized the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). ICOADS is a data set of global marine surface conditions and locations, collected and reported by a fleet of about 4000 ships known as the Voluntary Observing Ships (VOS) [21]. For this study, an improved ICOADS data set representing a proxy for global ship traffic was visually examined in order to identify areas of steady ship traffic within the study area [22]. In Fig. 3, these data are displayed in $0.1° \times 0.1°$ grids. As can be seen in Fig. 3a, at the Atlantic Ocean scale clear economic shipping lanes are apparent, while an examination at the scale of the Maryland study area (Fig. 3b) reveals a less-clear picture of habitual traffic patterns.

While it is difficult to define exact shipping routes through the Maryland study area, we set somewhat arbitrary lanes of 'potential conflict' based on a combination of the Ship Emissions Allocation Factor (SEAF) intensity in each grid [23] and the qualitative understanding of habitual routes gained from a global and regional view of the data. These designated conflict areas are shown in Fig. 4. Ship traffic in the study area is going past the coast, not stopping, as there is no port on Maryland's Atlantic coast. Thus, potential shipping conflicts are more likely in deeper water, in the areas of jacket and floating technologies, with a relatively small area of potential conflict in waters of monopile-appropriate depths. Here, we do not calculate shipping conflict area by water depth, but rather as a total for the entire study area (Table 3).

2.1.4. Environmental exclusions

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 [24], and others. In this study we only consider potential avian impacts based on location; proper offshore wind development planning will require data collection on avian species composition and location. In consultation with avian specialists, it was determined that Maryland's coastline is part of the Atlantic flyway, a route taken by migratory birds flying north and south, and that an exclusion zone one nautical mile wide parallel to the coastline should be implemented because migratory birds tend to follow the coastline [25]. This biological consideration is important, but in this case was redundant with the visual exclusion analysis explained in Section 2.1.5.

No biological exclusion areas were defined for marine mammals, because evidence to date is that the primary impact is during construction, e.g. the noise of pile driving, which is mitigated by construction practices not by changing location of construction. The biological exclusion zones are shown in Fig. 4, along with others discussed below.

2.1.5. Visual exclusions

Visual impacts, in conjunction with other social factors, have motivated opposition to offshore wind, notably the Cape Wind Project off Cape Cod, Massachusetts [26]. Visual impacts could potentially decrease tourism revenue if people choose to stop visiting a beach when turbines become visible. No quantitative studies have been conducted of these effects in Maryland, however a study has been conducted in Delaware, a neighboring coastal state with similar beach tourism. The University of Delaware's Center for Carbon-free Power Integration conducted a public opinion survey of Delaware residents to determine willingness-to-pay associated with the placement of wind turbines at various distances from shore [27,28]. Survey respondents were shown visualizations, simulating the way turbines would appear at different distances. The study found that even coastal residents, the group with the highest valuation of uninterrupted views, reported very little additional willingness-to-pay for moving turbines beyond 9 miles (8 nautical miles) offshore [27,28].[2]

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[2] 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 less than one nautical mile from shore before those residents would prefer new fossil fuel development [29].
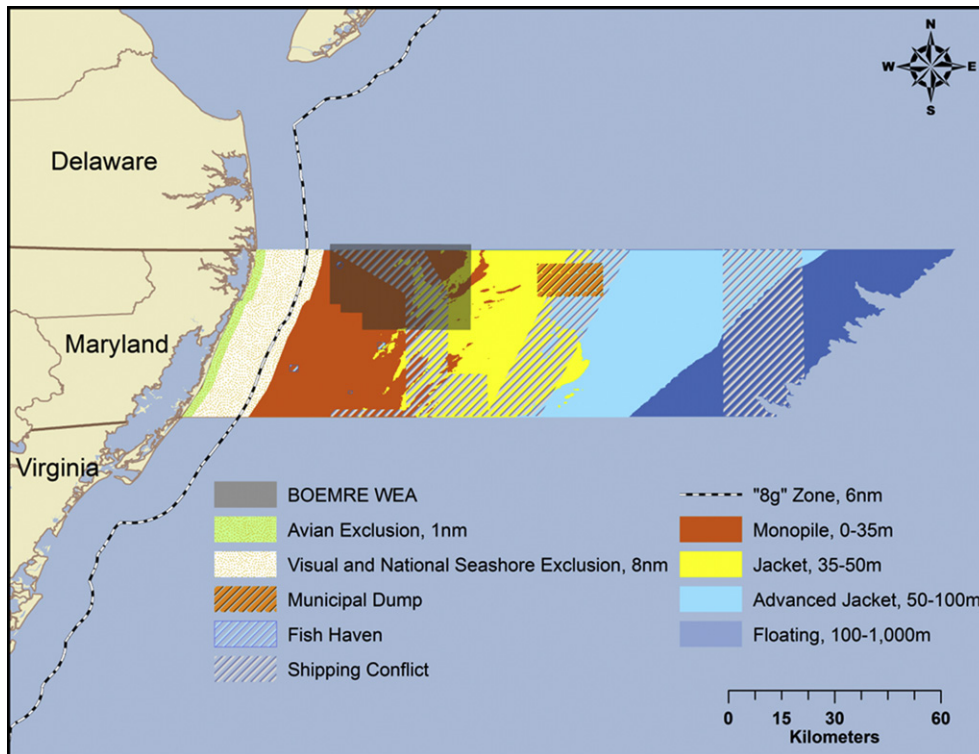
Fig. 4. Exclusion zones and potential shipping conflict areas within the Maryland study area. Also included is the BOEMRE WEA. Notice the overlap of the WEA and the shipping conflict.

These findings provide a range of more and less tolerable values, but do not provide a definitive answer in how far wind turbines should be from shore. In order to err on the side of low tolerance for visual impact, two 8-nautical mile exclusion zones, each in the shape of a semi-circle, were initially applied around the tourism destinations of Ocean City, MD and Assateague Island National Seashore.[3] The overlap of these two semi-circles was so great, however, that an 8-nautical mile exclusion zone was applied along the length of the Maryland shoreline. Both the avian exclusion and the visual exclusion can be seen in Fig. 4. In the methods diagram, the competing uses are represented as Fig. 1; Box C, and the remaining available area is shown as Fig. 1; Box D.

In addition to the exclusion zones, Fig. 4 shows a line labeled "8g". This is the boundary for revenue sharing between states and the federal government. There is a financial incentive for states to locate wind turbines within this boundary.[3] In this study turbines were illustratively excluded from within the 8g line to minimize visual impact, however this was done as a conservative resource estimate not a recommendation or prediction. As a counterexample, a project in advanced permitting off New Jersey (by Fisherman's Energy, LLC) is closer than 3 nautical miles and has not

generated any notable public opposition. Fig. 4 also shows the BOEMRE WEA, which will be discussed in section 3.3.

2.2. Calculating offshore wind power potential

2.2.1. Analysis of the wind resource

NOAA maintains meteorological buoys throughout the United States' Exclusive Economic Zone (3–200 nm) that record information about marine conditions including water and air temperature, wind speed and direction, and wave height (Fig. 1; Box E). The hourly interval data are available to the public from the NOAA National Data Buoy Center [30]. The records for many buoys extend twenty years; however there are gaps due to instrument malfunctions. To ensure accurate results when working with multiple buoys it is necessary to select years when the data are available across all buoys. Another problem is the sparsity of buoys; 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 two year's worth of data. To assess the study area wind regime, wind data was interpolated from the three sites shown in Fig. 2a: Buoy 44009, the offshore platform CHLV2, and Buoy 44014. The locations of these weather stations range from 10 nm to 50 nm offshore. However, the ocean wind speeds are far more evenly distributed than those over land. Thus, as we will note below, use of the single buoy 44009 was sufficiently accurate for this resource estimate.

The buoy wind speeds were extrapolated from their respective anemometer heights of 5-m (buoy 44009 and 44014) and 43.3-m (platform CHLV2) to the turbine hub height of 90-m, the height currently being used or expected for a typical offshore wind turbine. A 5 MW turbine was selected as a representative current-generation size. Wind speeds were extrapolated using the log law (Fig. 1; Box F):

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[3] These near shore areas have been excluded in this article's calculation in order to provide a conservative estimate of Maryland's offshore wind resource size. However, 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 states like Maryland have greater control over development within state waters—the first three nautical miles from shore—and states obtain part or all the royalty revenues from projects within six nautical miles of its shore, Maryland may wish to consider nearer-shore offshore wind power development than that used here for exclusion area calculations. (See Federal Register, Vol. 74, No. 81, pp. 19638–19871 (April 29, 2009), to be codified in pertinent part in the Code of Federal Regulations (CFR) at Vol. 30, Sections 385.540–385.543).
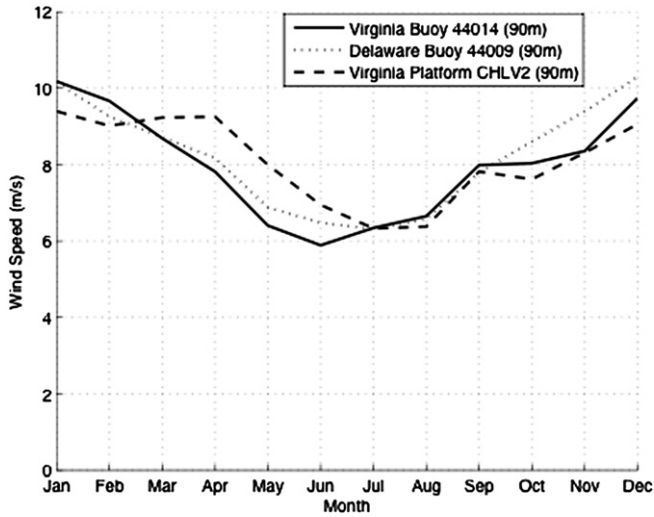
Fig. 5. Monthly average wind speeds at 90 m hub height, extrapolated and averaged from eleven years of data for three meteorological stations near the study area.

$$U(z)/U(z_r) = \ln(z/z_o)/\ln(z_r/z_o) \tag{1}$$

For Eq. (1), $U(z_r)$ is the recorded wind speed, z is hub height, z_r denotes the anemometer height (available for these data on the NOAA website), and z_0 is the surface roughness. A theoretically derived surface roughness value of the Atlantic Ocean of $z_0 = 0.188$ mm was used for the study [31]. This surface roughness value is comparable to the accepted z_0 value of 0.2 mm for a calm sea [32].

The average monthly wind speeds of the three buoys, extrapolated to 90 m, are displayed in Fig. 5; the figures show that the three sites have similar values throughout the year. A t-test shows that the means of the three different wind distributions, constructed from eleven years' data, are not statistically different ($p < 0.05$). The wind direction correlations between the three buoys were not analyzed because the primary focus of this study is power output.

Because the wind speeds of the three meteorological stations are not statistically different, data from the closest buoy, Buoy 44009, were used as an estimate of wind speed throughout the
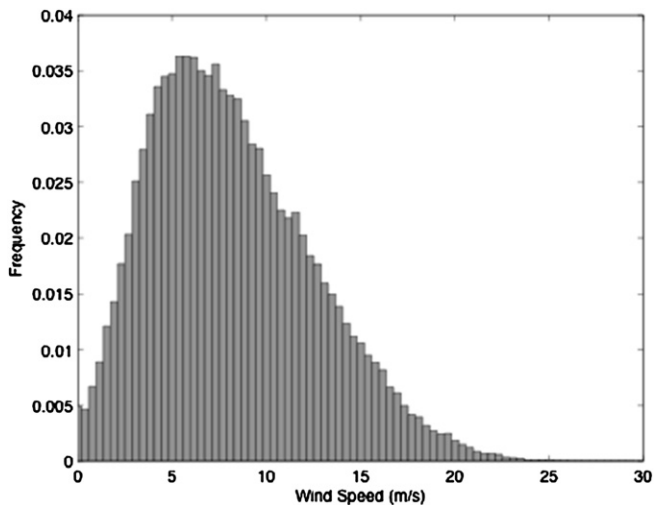

Fig. 6. Hub height wind speed distribution extrapolated from Buoy 44009 over eleven years. The bin sizes are 0.4m/s.

study area. The hub height wind speed distribution from Buoy 44009 is presented in Fig. 6. The eleven-year average wind speed at hub height of Buoy 44009 is 8.19 meters per second (m/s) with a standard deviation of 4.3 m/s.

2.2.2. Calculating wind power output

To project power output from wind speed, the power curve from one representative offshore-class 5 MW machine, the REpower 5M [33], was used to convert hourly wind speeds into hourly power in kW_a. Since wind speed-readings are averaged for each hour the power values are average for an hour as well. Thus, each hour's power output is equal to the number of kWh of energy produced during that one hour. Hourly energy production was then summed into annual totals, from which capacity factor (CF) was calculated using Eq. (2).

$$CF = \text{Annual Energy Production(kWh/year)}/(\text{RatedPower(kW)} \times 8760\,\text{h/year}) \tag{2}$$

The capacity factor for a sample turbine using the extrapolated wind speeds at buoy 44009 is 0.42 (before accounting for wake effect and availability). This gives an average power output for our example turbine of 2070 kW_a (Fig. 1; Box G). In order to determine the required spacing and layout orientation between turbines to ensure optimum energy generation at a given location, the prevailing wind direction was analyzed. These data were included in the meteorological buoy data, thus it was possible to separate the wind resource into bins according to the direction of the wind. Dividing wind directions into 5-degree intervals produced 60 bins. For each bin, the direction-specific wind power resource was characterized by three parameters:

The amount of time that the wind blows from each direction in an average year (the "frequency") was determined by counting the total number of data points within that bin.

The average wind speed for each wind direction was calculated by averaging the wind speeds of data points within that bin.

The average power output for each wind direction was calculated by averaging the power output of data points within that bin.

Seasonal rose plots of these three variables are shown in Fig. 7. For each wind rose of Fig. 7, eleven years' worth of season-specific data are complied. To illustrate the contrast in wind regimes between seasons, the magnitudes of the Power and Speed plots are scaled by the maximum directional power and speed of the year, found in winter, while the magnitude of the Frequency plots are scaled by the maximum directional frequency value of the year, found in summer.

Average power output is highest during the winter season (December, January, February) from winds out of the northwest. Autumn (September, October, November), spring (March, April, May), and summer (June, July, August) are progressively less windy; however as noted above, the summer months have the most consistent wind direction from the southwest.

To take advantage of the strongly directional wind patterns developers may want to make directional considerations in specific turbine placement. For a given wind direction, total energy output can be optimized by positioning turbines in rows, each five rotor diameters apart crosswind and ten rotor diameters apart downwind. The wind rose can be used to determine how to align turbine rows. While a full economic analysis is beyond the scope of this study it should be noted that electricity demand and spot market prices tend to be greatest in the summer. Consequently it may be
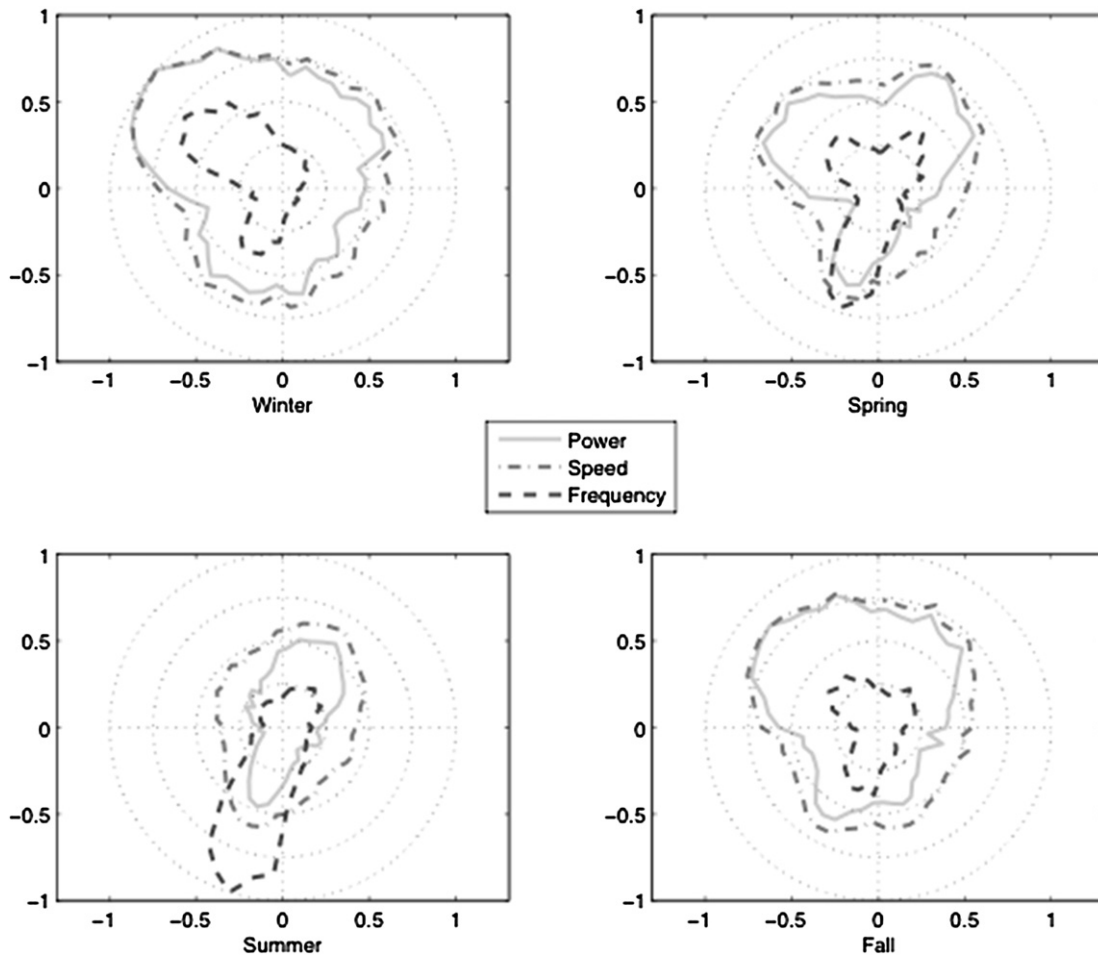
Fig. 7. Seasonal Wind Rose Plots depicting extractable wind power, hub height wind speed, and wind frequency by direction. The values are normalized by the maximum yearly values.

worthwhile for developers to consider siting the turbine rows to take advantage of southwesterly summer winds. Another option would be to orient turbines for north-northwest winds, to optimize year-around power generation.

The effective footprint per turbine (Array Spacing) is calculated using Eq. (3).

$$\text{Array Spacing} = (\text{rotor diameter})^2 \times \text{downwind spacing factor} \\ \times \text{crosswind spacing factor} \tag{3}$$

The rotor diameter of the example REpower 5M turbine is 126 m and for directional emplacement the crosswind and downwind spacing factor are 5 and 10 rotor diameters, respectively, yielding an array spacing of 0.794 km². Therefore, one square kilometer of ocean area accommodates 6.3 MW of installed capacity.

3. Results

3.1. Energy production

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

Using the array spacing of 0.794 km², the number of turbines that could be installed at each depth is calculated as shown in Eq. (4) (Fig. 1; Box H).

$$\text{Number of turbines} = \text{total available area} \div \text{array spacing} \tag{4}$$

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.

In decision-making contexts, it is often necessary to compare renewable energy resources such as offshore wind to traditional generation sources (i.e. coal, nuclear, natural gas). In such a comparison, it is more useful to use the 'average output' than the installed nameplate capacity. Average output is computed by multiplying the nameplate capacity by the capacity factor.[4] The

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[4] Here, we use an 'all-in' capacity factor of 0.3406, which includes wake effect losses and wind turbine availability. Traditional generation sources (coal, gas, nuclear) have high availability and high capacity factors. Generally speaking, these generators have capacity factors in the 0.70–0.95 range. Thus, an offshore wind project with a 500 MW nameplate capacity would have an average output of 170 MW$_a$; a coal plant with the same nameplate capacity would have an average output of approximately 370 MW$_a$ (according to the United States Energy Information Agency, the 2007 average capacity factor for coal plants was 0.74 and nuclear 0.92).

Table 2
Available area, power potential, and energy generation by depth. The potential energy generated from offshore wind as a percentage of Maryland's electric load in 2007 is also shown.

Depth (m)	Available area (km^2)	Wind turbines	Nameplate capacity (MW)	Average output (MW$_a$)	Total annual generation (MWh/year)	Percentage of MD load, 2007 (cumulative by depth)
0–35	2322	2925	14,625	5254	46,023,049	70%
35–50	2310	2910	14,550	5227	45,787,033	140%
50–100	2723	3430	17,150	6161	53,968,909	223%
100–1000	2171	2734	13,670	4911	43,017,783	289%
Total	**9526**	**11,999**	**59,995**	**21,552**	**188,796,774**	

Table 3
Power potential and energy generation from the entire Maryland study area before and after subtracting shipping conflict areas.

	Available area (km^2)	Wind turbines	Nameplate capacity (MW)	Average output (MW$_a$)	Total annual generation (MWh/year)	Percentage of MD load, 2007 (0–1000 m)
Before subtracting shipping conflict areas	9526	11,999	59,995	21,552	188,796,774	289%
After subtracting shipping conflict areas	6226	7843	39,214	14,087	123,401,562	189%

average output corresponds to the average power generated over the course of the year. In the absence of the primary hourly data, total annual energy generation can be calculated by multiplying the average output by the number of hours in a year (8760).

To generate a more accurate estimate of average power output and average annual energy production, the wind-based capacity factor must be derated to account for 'wake effect' and 'availability' (Fig. 1; Box I). Wake effect refers to the reduction in generation due to increased turbulence caused by windward turbines. Availability is the fraction of time that a wind project is ready to operate, taking into account planned and unplanned outages (e.g., scheduled maintenance, unplanned shutdowns, and weather events preventing maintenance). A wake effect of 10% average power reduction [34] and an availability of 95% [35] were used as indicated in Table 2.

Given the available area after exclusions, the wind analysis described above, and the derating factors for wake effect and turbine availability (Fig. 1; Box J), Maryland has the potential to install almost 60,000 MW of offshore wind capacity. This would produce an average power output of 21,552 MW$_a$, or 188 million MWh of energy per year. Using commercially mature, proven technology in shallow waters, there is potential to install 14,625 MW of capacity, and generate 5254 MW$_a$ on average.

For reference, the potential resource off Maryland's Atlantic coast can be compared with the state's electricity demand. Maryland's total retail electricity sales in 2007 were 65,390,660 MWh, thus, the state's average electricity consumption was 7465 MW$_a$ [36].

Table 2 can be used to compare different development options. For example, development within the 0–35 m depth range, including a visual exclusion zone of 8 nautical miles from shore, allows the potential to site nearly 3000 turbines, which on average could supply 70% of the Maryland electric load. Considering a depth of 0–50 m, offshore wind has the potential to fulfill 140% of Maryland's load. If fully developed out to 1000 m depth, offshore wind power has the potential to generate 188,000,000 MWh per year, over two and a half times Maryland's electric consumption of 65,391,000 MWh/year. The full results are presented in Table 2. In order for wind to fulfill such large portions of the load, innovative integration solutions may be required. Integration solutions include interconnecting wind projects in complementary wind regimes [37], storage and load balancing in electric vehicles through Vehicle-to-Grid (V2G) [38], or centrally via flow batteries or compressed air energy storage (CAES) [39]. Such solutions are already national priorities [40].

3.2. Energy production excluding potential shipping conflict areas

The total area in which offshore wind development could conflict with commercial shipping is 3300 km^2. Subtracting this value from the previous total available area provides an estimate of the total available area for offshore wind development. As shown in Table 3, the total area available for offshore wind development, when taking into account commercial shipping conflict areas and the exclusions detailed in section two of this report, is 6226 km^2. This area translates into average annual generation of more than 123,000,000 MWh/year.

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

3.3. BOEMRE wind energy area

In November 2010, the federal agency that issues Outer Continental Shelf (OCS) leases, BOEMRE, released a Request for Information for offshore wind development off the Maryland Coast. The 200 square nautical mile area of the OCS is a priority Wind Energy Area (WEA), available for lease to offshore wind developers. However, as Fig. 4 illustrates, the designated WEA is located in an area of high ship conflict. In fact, the Maryland WEA lies at one end of a designated shipping lane into and out of the Delaware Bay. As previously mentioned, ships do not randomly disperse after exiting the shipping lane but rather follow the shortest path to their next destination, which, in this case, may go directly through the WEA. Under pressure from maritime organizations, BOEMRE reduced the WEA by two-thirds without any apparent cost-benefit analysis or evaluation of how such a dramatic size reduction might affect wind project viability. In the future BOEMRE should consider the interaction between offshore wind, established shipping lanes, and habitual shipping routes, and the relative costs imposed on each industry.

4. Conclusion

The results of this preliminary study indicate that Maryland's feasible offshore wind resource (including both state and federal waters) is large enough to significantly contribute to the electric demands of the state. Using existing, commercially proven

technology (monopile foundations in shallow waters) and accounting for various social, environmental, and nautical exclusions and potential conflict areas, Maryland's available offshore wind resource could provide 70% of the state's electric load.[5] Using prototyped but not yet commercially proven deeper water technology, Maryland's offshore wind resource is sufficient to provide 189% of the state's electric load. The size of this resource is dependent on the size of zones excluded due to conflicting uses. The calculated resource size would be larger if part of the 8-nautical mile area nearest to shore were also developed, or if floating turbines were used at depths of more than 1 km. On the other hand, it would be substantially reduced if significant areas of the study site were set aside for military use, as one source has suggested [15].

The offshore wind resource thus represents an opportunity for Maryland to generate most of its electricity without importing fuel, to drastically reduce CO_2 emissions from the state's electric power sector, and increase air quality in the region. Offshore wind power also generates the Renewable Energy Credits (RECs) needed by electric utilities to comply with the state's Renewable Portfolio Standard (RPS). The RPS is a law which 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 would require a total of 3900 MW, that is, installing an average of 300 MW capacity per year. Over half of the fifty states in the U.S. have similar RPS policies; nineteen of those are coastal states with offshore wind potential.

Currently, no other Tier 1 renewable resource available in the East is as low cost as wind power. Nevertheless, offshore wind power is still more expensive than the market price of energy. Offshore wind is also more expensive than onshore wind power, but the latter is too small in the Eastern states, like Maryland, to meet their RPS requirements. The current cost of offshore wind can be inferred from two recent power purchase agreements for offshore wind energy in Delaware and Massachusetts, both higher than the average cost of electricity in those states, and higher than nearby onshore wind contracts [41]. However, the U.S. Department of Energy (DOE) has released a strategic plan to meet the goals of developing 10 GW of offshore wind power at a cost of US$130/MWh by 2020 and 54 GW at a cost of between US$70 and 90/MWh by 2030 [42]. The 2020 figure may be slightly higher than parity with market electric prices at that time but still competitive given the mandate for renewable energy at the state level. The 2030 figure is likely to be on par or slightly lower cost than competing generation technologies. The DOE plan suggests that these cost goals would be achieved by technology development, more efficient deployment, and mass production.

This leaves two policy questions for coastal states. One question is, do states want to meet their RPS requirements primarily from offshore wind, since it is large enough to meet the full RPS requirement at relatively low cost? Or, exhaust all onshore wind first? Going beyond the RPS requirements, do coastal states want to begin permitting large-scale offshore wind power production now, possibly gaining early market and industrialization advantage at a higher cost of electricity, or wait until prices are lower but other states have captured more of the industrial development?

The method demonstrated here is useful for providing realistic offshore wind resource estimates in a publicly accessible manner.

Typical prior wind resource assessments only give wind speeds over a map of the study area. At this study site, the wind speeds were found to be fairly uniform over state-sized areas, so the resource estimate depends more upon how much ocean area could be available for turbine installation than on precise wind speeds. Additionally, to communicate more clearly to decision-makers, we feel it is important to report resource in average power production terms, instead of in wind speed or capacity terms.

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