Large CO\textsubscript{2} reductions via offshore wind power matched to inherent storage in energy end-uses

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[1] We develop methods for assessing offshore wind resources, using a model of the vertical structure of the planetary boundary layer (PBL) over water and a wind-electric technology analysis linking turbine and tower limitations to bathymetry and continental shelf geology. These methods are tested by matching the winds of the Middle-Atlantic Bight (MAB) to energy demand in the adjacent states (Massachusetts through North Carolina, U.S.A.). We find that the MAB wind resource can produce 330 GW average electrical power, a resource exceeding the region’s current summed demand for 73 GW of electricity, 29 GW of light vehicle fuels (now gasoline), and 83 GW of building fuels (now distillate fuel oil and natural gas). Supplying these end-uses with MAB wind power would reduce by 68% the region’s CO\textsubscript{2} emissions, and reduce by 57% its greenhouse gas forcing. These percentages are in the range of the global reductions needed to stabilize climate. Citation: Kempton, W., C. L. Archer, A. Dhanju, R. W. Garvine, and M. Z. Jacobson (2007), Large CO\textsubscript{2} reductions via offshore wind power matched to inherent storage in energy end-uses, Geophys. Res. Lett., 34, LXXXXX, doi:10.1029/2006GL028016.

1. Introduction

[2] Recent findings on anthropogenic atmospheric carbon dioxide (CO\textsubscript{2}) and near-term commitment to the global change it will bring [Caldera and Wickett, 2003; Gregory et al., 2004; Thomas et al., 2004] increasingly appear to require a response faster than that of historic energy system transformations. The short time scale necessitates deployment of existing and new technologies. Oceanic winds vary with latitude, with weaker winds near the equator and stronger oceanic winds from the polar air masses through the mid-latitudes, including the populous eastern coasts of Asia and North America (NASA Surface meteorology and Solar Energy: Methodology, 2004, http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?na+s06#s06). Within those latitudes, regional offshore winds are remarkably uniform (R. Garvine and W. Kempton, The wind field over the ocean as a resource for electric power, manuscript in preparation, 2006) hereinafter referred to as Garvine and Kempton, manuscript in preparation, 2006). Thus, the oceanic wind resource is unlike minerals or terrestrial winds. It is not restricted to select locations—it is relatively uniform through a region. Thus, resource location and assessment become an inverse problem, of understanding exclusions and limitations on turbine placement, e.g., wind tower technology limits on water depth, competing human uses of ocean space, and wildlife or ecological vulnerabilities.

[3] To develop and test a systematic oceanic wind assessment, we select an area off the United States especially suitable for offshore turbines, due to large shelf and lack of category 5 hurricanes. This is the Middle Atlantic Bight (MAB), a broad sand and gravel shelf of slope 0.001 extending from Cape Hatteras to Cape Cod. Here we analyze a slightly expanded area, 34° N to 43° N, aligning with the US states of North Carolina through Massachusetts (Figure 1).

2. Model of Wind Speed in PBL

[4] Estimating wind resources over water is fundamentally different from estimating mineral resources or wind resources over land. The location of minerals, and of most terrestrial winds, are determined respectively by geological processes and topography. Oceanic wind speeds vary with latitude, with weaker winds near the equator and stronger oceanic winds from the polar air masses through the mid-latitudes, including the populous eastern coasts of Asia and North America (NASA Surface meteorology and Solar Energy: Methodology, 2004, http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?na+s06#s06). Within those latitudes, regional offshore winds are remarkably uniform (R. Garvine and W. Kempton, The wind field over the ocean as a resource for electric power, manuscript in preparation, 2006) hereinafter referred to as Garvine and Kempton, manuscript in preparation, 2006). Thus, the oceanic wind resource is unlike minerals or terrestrial winds. It is not restricted to select locations—it is relatively uniform through a region. Thus, resource location and assessment become an inverse problem, of understanding exclusions and limitations on turbine placement, e.g., wind tower technology limits on water depth, competing human uses of ocean space, and wildlife or ecological vulnerabilities.

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near-surface anemometer measurements to hub height by across buoys of only 0.8 m/s. These are shown in auxiliary "OWEC Jacket Quattropod", has been validated for 50 m Haugsøen mean wind speed of 7.8 m/s, to represent MAB estuaries wind speed (and below the mean power output). This buoy, use Delaware Bay weather stations sj and bs, with combined simplify the electric power estimation by sampling a single KEMPTON ET AL.: OFFSHORE WIND POWER LXXXXX

[Table S3]

MAB show a mean of 8.3 m/s (at 80 m height) with SD accounting for stratification, Coriolis parameter (fixed by the latitude), and the geostrophic wind speed and direction extrapolation are used. Given this uniformity, we greatly ocean areas of the entire MAB. We take 21 years of readings at 44009, exclude missing hours (157,079 hours of valid data), and obtain hourly wind speeds. Similarly, we use Delaware Bay weather stations sj and bs, with combined mean wind speed of 7.8 m/s, to represent MAB estuaries (see Figure 1).

3. Bathymetric Areas, Exclusion Areas, and Turbine Spacing

[8] We consider only bottom-mounted wind technology, as floating structures have not been prototyped. Two tower technologies are relevant for water depths beyond a few meters. The tubular steel monopile driven into the bottom is proven to depth of 20 m. A new lattice structure, the "OWEC Jacket Quattropod", has been validated for 50 m water depth and installed in 45 m [Seidel and Foss, 2006]. It plausibly scales to 100 m [Haugsoen, 2006] (slides at www.ivt.ntnu.no/bat/mb/vindkraft/index.htm) and its cost increases only linearly with depth. Thus, we analyze three bathymetric intervals, corresponding to mounting technolo-gies that are, respectively, current industry practice (0–20 m), prototyped and operating in the ocean (20–50 m), and a scale extension of existing technology (50–100 m). Figure 1 shows these bathymetric regions. Their combined areas, given in Table 1, total 190,300 km².

[9] Part of the areas in Figure 1 are not available for placement of wind turbines due to competing uses given higher priority for regulatory, political or economic reasons [Firestone et al., 2004; Kempton et al., 2005]. Full account-ing of exclusion areas for the MAB would require a large effort drawing on multiple databases and interviewing. Pend-ing such an effort, we draw on the recent analysis of a sample oceanic and estuary area off the state of Delaware by A. Dhanju et al. (Assessing offshore wind resources: An accessible methodology, submitted to Renewable Energy, 2006) (hereinafter referred to as Dhanju et al., submitted manuscript, 2006) to obtain a realistic “exclusion fraction” at each depth range. They excluded major bird flyways, ship-ping lanes, areas of oceanic ship passage outside of shipping lanes, chemical disposal sites, military restricted areas, zones of unexploded mines, borrow areas for beach renourishment, and visual space from the one major tourist beach. No conflict with commercial or recreational fishing is expected (Dhanju et al., submitted manuscript, 2006). Many of these areas overlap. Our calculated exclusion fractions at each bathymetric interval for the sampled area are shown in Table 1 (also see auxiliary materials), yielding the remaining ocean area available.

[10] All turbines under consideration for new U.S. offshore projects are over 3 MW. The only 3 MW machines already tested in the ocean are the General Electric 3.6s and the REpower 5M, with “nameplate power” (maximum output) of 3.6 MW and 5 MW, respectively. Blade diameters are 104 m and 126 m, respectively. To minimize inter-turbine wake losses, we impose minimum spacing of 10 167 rotor diameters downwind, and 5 cross-wind [Manwell et al., 2002]. This spacing corresponds to 0.54 km² per 168 3.6s turbine (close to the value for the Cape Wind layout [U.S. Army Corps of Engineers, 2004]), or 0.79 km² per 171 5M. These yield the turbine counts in Table 1.

4. Power Output

[11] To calculate power output, we use the published power curve of each manufacturer, giving power output as a 176 function of wind speed. The best fit function was a 177 combination of two 3rd order polynomials, mapping hourly wind speed to power output. Average output power is a 178 more useful resource measure than nameplate power capac-

ity. Offshore wind operating experience shows < 2% turbine downtime for maintenance [Larsen et al., 2005], mostly scheduled at low wind times, so we ignore this factor. 182

[12] Using the multi-year wind speeds from section 2 as input to the power equations, we find average output for the GE 3.6s is 1.420 MW, and for the REpower 5M is 1.987 MW, corresponding to capacity factors for these 186 turbines in the oceanic wind regime of 0.394 and 0.397, respectively. A similar calculation for the estuaries of the 188
MAB, also sampled, yields mean power for each machine of 1.28 MW and 1.79 MW, or capacity factors about 0.36. From the turbine count and power per turbine (ocean + estuary), we find the region’s average power output to be 344 GW or 330 GW (Table 1). This is three times a prior unpublished approximation of 260 GW nameplate power, which did not analyze bathymetry, exclusion areas, or average output [Musial, 2005]. We use our lower power figure, 330 GW average output, to compare first with regional fossil fuel resources, then with power demand. (Average power output can be multiplied by 8760 h/y to yield annual energy produced in GWh/year.)

Table 1. Calculated Surface Area (Ocean + Estuary), Exclusion Fraction, and Power for the Depth Regions of the MAB in Figure 1

<table>
<thead>
<tr>
<th>Ocean + estuary area (km²)</th>
<th>Exclusion fraction</th>
<th>Remaining area available (km²)</th>
<th>3.6 s average output (GW)</th>
<th>5M turbines (count)</th>
<th>5M average output (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31,900 + 13,600</td>
<td>46</td>
<td>17,226 + 7,344</td>
<td>45 + 17</td>
<td>21,805 + 9296</td>
<td>43 + 17</td>
</tr>
<tr>
<td>75,260 + 2140</td>
<td></td>
<td>45,156 + 1,284</td>
<td>119 + 3</td>
<td>57,159 + 1,625</td>
<td>114 + 3</td>
</tr>
<tr>
<td>67,400</td>
<td></td>
<td>60,660</td>
<td>160</td>
<td>76,835</td>
<td>153</td>
</tr>
<tr>
<td>190,300</td>
<td></td>
<td>124,300</td>
<td>344</td>
<td>166,720</td>
<td>330</td>
</tr>
</tbody>
</table>

*Power is average output, not nameplate capacity, over 21 years of wind speed at 80 m hub height for a sampled mid-range buoy.

5. Matching Oceanic Wind to Human Energy Use

Table 2. Power Source Comparison: Wind, Oil, and Gas off the U.S. East Coast, If Used to Generate Electric Power

<table>
<thead>
<tr>
<th>Offshore Wind in MAB</th>
<th>Oil in Atlantic OCS</th>
<th>Gas in Atlantic OCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (native units)</td>
<td>835 GW</td>
<td>3.8 · 10⁹ BBL⁸</td>
</tr>
<tr>
<td>Resource lifetime (years)</td>
<td>∞</td>
<td>20</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>395</td>
<td>n.a.</td>
</tr>
<tr>
<td>Power at source (GW units)</td>
<td>330</td>
<td>37</td>
</tr>
<tr>
<td>Delivered power (GW)</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Delivered power (GW)</td>
<td>297</td>
<td>18</td>
</tr>
</tbody>
</table>

with load. Because wind speed cross-correlation drops with distance [Giebel, 2000], distributed wind resources, connected by electrical transmission lines, produce more level power than their individual constituent sites [Kahn, 1979; Milligan and Factor, 2000; C. L. Archer and M. Z. Jacobson, Supplying baseload power and reducing transmission requirements by interconnecting wind farms, submitted to Journal of Applied Meteorology and Climatology, 2006]. Figure 2 shows this via generation duration curves of up to 6 MAB wind sites. The hourly power output of turbines at 1, 3, and 6 sites, all normalized to a single 3.6 MW turbine, is plotted in left-to-right order of hours from highest to lowest power. For each number of sites, the best combination of sites is picked, based on the most consistent capacity during summer peak load hours. Figure 2 shows that for the single site (black line), 13% of hours are at maximum output but 15% of hours are off (below cut-in speed of 3.5 m/s). For 3 and 6 connected sites, the power is off only 2% and 0.3% of the hours, respectively. Since the off-time for all multi-site combinations is well under the 6% forced outage time for baseload fossil generators [North American Electric Reliability Council, 2005], it is incorrect to call power from these interconnected offshore wind sites “intermittent.” Rather, the problem is that the fluctuations in the wind resource are not matched to fluctuations in load, whereas fossil plants are scheduled to match load.

[17] There are several ways to match fluctuating supply to load without the expense of building dedicated storage or backup generation; here we suggest one combination of methods as an illustration. A light vehicle fleet of battery, plug-in hybrid and/or hydrogen fuel cell vehicles would have substantial energy storage, which could be controlled by the electric grid operator when the vehicle is idle and plugged-in [Kempton and Tomic, 2005a]. Assume 2/3 of the 29 · 10^6 registered automobiles in the MAB region [U.S. Census Bureau, 2006] were electrified with 30 kWh storage, and assume that at any one time when needed, only half of these electrified vehicles could respond, each providing half their storage. This is a 145 GWh storage resource, capable of carrying the average 73 GW electrical load for 2 hours. Prior analysis of one such large-scale example showed that electrified vehicles would be sufficient for wind backup all but 5 times/year [Kempton and Tomic, 2005b]. For the occasions when vehicle storage is inadequate, today’s fossil fuel plants could be retained in standby mode and tapped several times per year. The inverse problem, excess wind power, would first supply any deferred demand for heat and vehicle battery charging; any subsequent remaining excess wind power would be sold on regional markets, or spilled.

7. Reduction in CO₂ Emissions

[18] The total effect of these changes in electric supply and end-use conversions on climate stabilization are estimated from US national data, assuming greenhouse gas (GHG) proportions by sector in the MAB region are similar to national ones [U.S. Energy Information Administration, 2004]. In 2004, US CO₂ emissions were 5973 · 10^6 metric tons (MMT), with CO₂ being 84% of the US anthropogenic GHG climate forcing. To estimate the effect of wind-supplied electricity, light vehicles and building fuels, we sum all energy-related emissions from the residential and commercial sectors, the gasoline fraction (60%) of transportation, and the electrical fraction (38%) of industrial. This sum is 1212 + 1024 + (.60 · 1934) + (.38 · 1730) = 4053 MMT, a reduction of 68% in CO₂ emissions (4053/5973), or of 57% in total anthropogenic GHG. The range of GHG reductions needed to prevent catastrophic effects of climate change is estimated to be a 60 to 80% reduction from 1990 levels. Our approach, comprehensive analysis of one resource in one region in conjunction with matched end-use fuel substitutions, yields a larger percentage GHG.

Figure 2. Generation duration curves for a single site (black) and for 3 (dark grey) and 6 (light grey) interconnected sites in the MAB. For each curve, the percentage of hours shows that the given number of sites will generate at least that much power.
reduction than a projected sum of 15 changes, not based on resource size nor regionally specific [Pacala and Socolow, 2004]. Additional comprehensive analyses, of resources and end-use substitutions in other regions, seem warranted.

[19] Acknowledgments. This work was supported by the UD College of Marine and Earth Studies, the Delaware Green Energy Fund, Delaware Sea Grant, and the Global Climate and Energy Project at Stanford University. We thank C. K. Sommerfield for insights on shelf geology, Brian Parsons and colleagues at NREL for advice on Peak Capacity Factor, and J. T. Reager and Michelle Overway for computational support.

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