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Large CO_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_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_2 reductions via offshore wind power matched to inherent storage in energy end-uses, *Geophys. Res. Lett.*, *34*, L02817, doi:10.1029/2006GL028016.

1. Introduction

[2] Recent findings on anthropogenic atmospheric carbon dioxide (CO_2) and near-term commitment to the global change it will bring [*Caldeira 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 beginning deployment with existing or prototyped technologies [*Pacala and Socolow*, 2004]. Wind-generated electricity is a very large, low-CO_2 resource [*Archer and Jacobson*, 2005], with technology already commercialized and economically-competitive [*Berlinski and Connors*, 2006]. Thus it holds the promise to significantly displace CO_2-emitting fuels within the available time. Here we assess the practical size of that resource over the ocean and its match to the energy demand of urbanized coastal states.

[3] From first principles, offshore wind should be of interest. Terrestrial wind resources are most abundant in mid-continental plains, but human populations concentrate along the coasts. The lower surface roughness of the ocean compared with virtually all terrestrial surfaces causes near-surface ocean winds to be faster and less variable [*Prior and Barthelmie*, 2002]. Disadvantages of offshore wind include: higher installation and maintenance costs in comparison with land sites, undeveloped regulatory regimes over water, technology not yet optimized for water locations, and immature offshore wind resource assessment methods. Here, we address the lattermost shortcoming.

[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 strongest 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.

[5] 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

[6] For wind speed, we extrapolate from anemometer data at 5–10 m height to the resource of interest, at the 80–100 m hub height of modern offshore turbines. For extrapolation, we use Garvine's solution for the surface roughness coefficient over the ocean surface (R. W. Garvine and F. Veron, A compact model of the neutral planetary boundary layer for ocean application, manuscript in preparation, 2006), which improves on prior estimates for extrapolating

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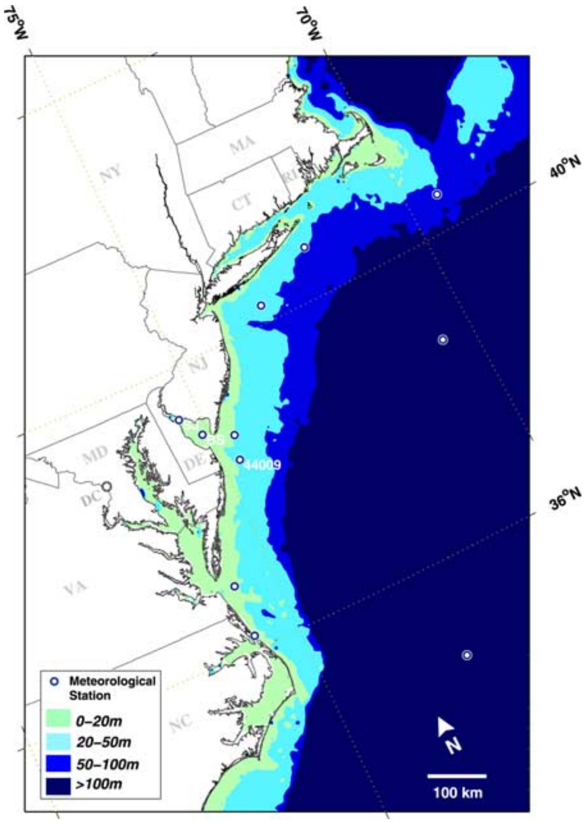

Figure 1. Depth areas of the Middle Atlantic Bight (MAB).

near-surface anemometer measurements to hub height by accounting for stratification, Coriolis parameter (fixed by the latitude), and the geostrophic wind speed and direction aloft.

[7] Wind speeds at all nine NOAA buoys in or near the MAB show a mean of 8.3 m/s (at 80 m height) with SD across buoys of only 0.8 m/s. These are shown in auxiliary Table S3[1], which also shows that our findings are not substantially different if older methods of wind speed extrapolation are used. Given this uniformity, we greatly simplify the electric power estimation by sampling a single buoy with mean 8.2 m/s, slightly below the MAB mean wind speed (and below the mean power output). This buoy, 44009, is used to estimate wind power across the open 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 [*Haugsøen*, 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 technologies 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 km^2.

[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 accounting of exclusion areas for the MAB would require a large effort drawing on multiple databases and interviewing. Pending 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, shipping 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 interturbine wake losses, we impose minimum spacing of 10 rotor diameters downwind, and 5 cross-wind [*Manwell et al.*, 2002]. This spacing corresponds to 0.54 km^2 per 3.6s turbine (close to the value for the Cape Wind layout [*U.S. Army Corps of Engineers*, 2004]), or 0.79 km^2 per 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 function of wind speed. The best fit function was a combination of two 3rd order polynomials, mapping hourly wind speed to power output. Average output power is a more useful resource measure than nameplate power capacity. 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.

[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

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[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl028016. Other auxiliary material files are in the HTML.

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

	0 to 20 m	20 to 50 m	50 to 100 m	Total
Ocean + estuary area (km^2)	31,900 + 13,600	75,260 + 2140	67,400	190,300
Exclusion fraction	.46	.40	.10	n.a.
Remaining area available (km^2)	17,226 + 7,344	45,156 + 1,284	60,660	131,670
3.6 s turbines (count)	31,900 + 13,600	83,622 + 2,378	112,407	243,907
3.6 s average output (GW)	45 + 17	119 + 3	160	344
5M turbines (count)	21,805 + 9296	57,159 + 1,625	76,835	166,720
5M average output (GW)	43 + 17	114 + 3	153	330

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

1.987 MW, corresponding to capacity factors for these turbines in the oceanic wind regime of 0.394 and 0.397, respectively. A similar calculation for the estuaries of the 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.)

[13] Comparing wind power with other regional resources, the oil and natural gas of the Atlantic Outer Continental Shelf (OCS), estimated as "undiscovered technically recoverable," is distributed over twice the area of the MAB, and comprises 6% of US OCS reserves. Table 2 compares wind, OCS oil, and OCS natural gas as sources of electricity. The diverse source energy units in Table 2 are converted to GW of electricity, assuming 20-years' production and losses in conversion to electricity and transmission as shown–yielding delivered electricity from each resource on the bottom row. The MAB wind resource offers over five times the electricity of the Atlantic OCS oil and gas, or over 10 times based on power per area.

5. Matching Oceanic Wind to Human Energy Use

[14] Next we compare the MAB wind resource with current regional electric load, as well as non-electric energy uses that could be substituted by electricity. The light vehicle fleet and low-grade heat in residential and commercial buildings are now supplied primarily by fossil fuels. They could be electrified by using battery and plug-in hybrid vehicles, resistance or heat pump space heating, water heating, electric cooking, etc. To minimize replacement costs, these end-use devices could be replaced at time of wearout, during deployment of the wind resource. If electrified, these loads would also improve the match between electrical load and wind supply, for four reasons: space heat is needed at times of greatest MAB wind supply (Garvine and Kempton, manuscript in preparation, 2006), space conditioning and water heat can be interrupted on an hourly scale under grid operator control [*Kempton et al.*, 1992], added thermal storage at end-use is typically inexpensive [*Ryle*, 1977; *Reddy et al.*, 1991], and vehicle batteries can be charged from and discharged to the grid with timing that matches wind to load [*Kempton and Tomić*, 2005a]. Here we do not address the many complexities of these end-use substitutions. Our first question is whether the MAB wind resource is of sufficient size to displace these end uses currently met by fuels.

[15] Table 3 gives electrical load, light vehicle fuels, and building fuels for the coastal states of the MAB (MA, RI, CT, NY, NJ, DE, MD, DC, VA, NC). Conversion and transmission losses are incurred in moving from the source to work: 0.25 oil well to driveshaft efficiency for the light vehicle fleet, and 0.7 or 0.8 for heating oil and natural gas to low-grade heat. Adding across the lowest row, total demand is 185 GW of delivered power. Assuming that wind electricity could deliver vehicle shaft power at 0.75 efficiency and building heat at 0.9 efficiency (assuming electric resistance heating), this would require 212 GW of electricity from the wind turbines. (The 0.75 efficiency of electric drive assumes plug-in battery vehicles—for H_2 fuel cell vehicles the efficiency is 0.25, so an H_2 fleet would require three times the source electricity.) Thus, displacing all electricity plus all these fuel uses would consume, on average, 212 GW, or 64% of the 330 GW MAB wind resource. Thus, the wind resource offers a potential to displace all these end-uses, plus provide for 50% regional energy-use growth over the present.

6. Managing Fluctuating Wind Power Output

[16] To supply such a large fraction of electrical load, the fluctuating wind resource must be levelized and matched

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

	Offshore Wind in MAB	Oil in Atlantic OCS	Gas in Atlantic OCS
Capacity (native units)	835 GW	$3.8 \cdot 10^9$ BBL[a]	$37 \cdot 10^{12}$ cf[a]
Resource lifetime (years)	∞	20	20
Capacity Factor	.395	n.a.	n.a.
Power at source (GW units)	330	37	64
Efficiency to deliver electric power	.9	.5	.6
Delivered power (GW)	297	18	38

[a] Minerals Management Service, Offshore Minerals Management Program, Report to Congress: Comprehensive Inventory of U.S. OCS Oil and Natural Gas Resources (Report to Congress required by Energy Policy Act of 2005, Section 357, February 2006).

Table 3. Power Use of States Bordering the MAB for Electricity, Personal Transport, and Heat (MA Through NC, Plus DC)[a]

	Electric Load	Light Vehicles	Building Heat (Distillate Fuel Oil)	Building Heat (Natural Gas)
Demand at source (native units)	(mixed)	$601 \cdot 10^6$ BBL/y[b]	$162 \cdot 10^6$ BBL/y[c]	$2.21 \cdot 10^{12}$ cf/y[d]
Efficiency to convert & deliver	(mixed)	0.25	0.7[e]	0.8[e]
Delivered power to meet need (GW)	73	29	22[f]	61[f]

[a] Differing fuel units are converted to year-round average GW of power delivered at the site of work (e.g., delivered electricity, building heat, or vehicle drive shaft motion).

[b] US Energy Information Administration, State Energy Consumption, Price, and Expenditure Estimates (SEDS), "Table F1: Motor Gasoline . . . 2002" (http://www.eia.doe.gov/emeu/states/_seds_updates.html), 2006.

[c] Residential + commercial is $5.06 + 1.76 \cdot 10^9$ gallon distillate fuel oil in 2004. Energy Information Administration, Fuel Oil and Kerosene Sales 2004, DOE/EIA-0535(04), Tables 7 and 8 (November 2005).

[d] US Energy Information Administration, "Natural Gas Navigator", Natural Gas Consumption by End Use 2005. http://eia.doe.gov (Sept 2006).

[e] Based on space heating: annual fuel utilization efficiency (AFUE) of stock 0.5 to 0.75, AFUE for new code is 0.8; gas is about 0.10 better than fuel oil.

[f] Our use of year-round average power is a simplified but potentially misleading metric here due to the highly seasonal nature of these loads. A more complete analysis would compare the winter wind peak with space heat load peak.

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 Tomić*, 2005a]. Assume 2/3 of the $29 \cdot 10^6$ 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 Tomić*, 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 CO_2 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 CO_2 emissions were $5973 \cdot 10^6$ metric tons (MMT), with CO_2 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 $1212 + 1024 + (.60 \cdot 1934) + (.38 \cdot 1730) = 4053$ MMT, a reduction of 68% in CO_2 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

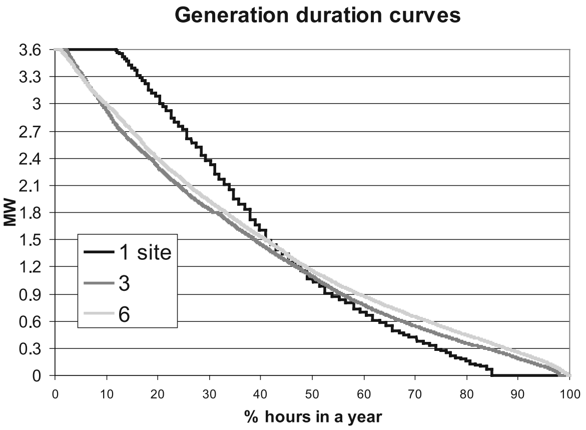

Figure 2. Generation duration curves for a single site (black) and for 3 (dark grey) and 6 (light grey) interconnected sites in the MAB. For each curve, the percentage of hours shows that the given number of sites will generate at least that much power.

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.

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