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Original
Where is the ideal location for a US East Coast offshore grid? / Dvorak, M. J.; Stoutenburg, E. D.; Lozej Archer, C.; Kempton, W.; Jacobson, M. Z.. - In: GEOPHYSICAL RESEARCH LETTERS. - ISSN 0094-8276. - 39:6(2012). [10.1029/2011GL050659]

Publisher:
American Geophysical Union

Published
DOI:10.1029/2011GL050659

GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L06804, doi:10.1029/2011GL050659, 2012

Where is the ideal location for a US East Coast offshore grid?

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Received 28 December 2011; revised 15 February 2012; accepted 20 February 2012; published 20 March 2012.

[1] This paper identifies the location of an "ideal" offshore wind energy (OWE) grid on the U.S. East Coast that would (1) provide the highest overall and peak-time summer capacity factor, (2) use bottom-mounted turbine foundations (depth ≤50 m), (3) connect regional transmissions grids from New England to the Mid-Atlantic, and (4) have a smoothed power output, reduced hourly ramp rates and hours of zero power. Hourly, high-resolution mesoscale weather model data from 2006–2010 were used to approximate wind farm output. The offshore grid was located in the waters from Long Island, New York to the Georges Bank, ≈450 km east. Twelve candidate 500 MW wind farms were located randomly throughout that region. Four wind farms (2000 MW total capacity) were selected for their synergistic meteorological characteristics that reduced offshore grid variability. Sites likely to have sea breezes helped increase the grid capacity factor during peak time in the spring and summer months. Sites far offshore, dominated by powerful synoptic-scale storms, were included for their generally higher but more variable power output. By interconnecting all 4 farms via an offshore grid versus 4 individual interconnections, power was smoothed, the no-power events were reduced from 9% to 4%, and the combined capacity factor was 48% (gross). By interconnecting offshore wind energy farms ≈450 km apart, in regions with offshore wind energy resources driven by both synoptic-scale storms and mesoscale sea breezes, substantial reductions in low/no-power hours and hourly ramp rates can be made. **Citation:** Dvorak, M. J., E. D. Stoutenburg, C. L. Archer, W. Kempton, and M. Z. Jacobson (2012), Where is the ideal location for a US East Coast offshore grid?, *Geophys. Res. Lett.*, *39*, L06804, doi:10.1029/2011GL050659.

1. Introduction

[2] Wind resources off the US East Coast have tremendous potential to reduce greenhouse gas emissions. The corridor from Maine to Florida is responsible for 34% of US electrical demand [*Energy Information Administration*, 2010], 35% of US CO_2 emissions [*Environmental Protection Agency*, 2010], and 36% of the US population [*U.S. Census Bureau*, 2009]. Additionally, the coastal transmission infrastructure is congested, making new, local generation that does not have to travel long distances over transmission lines a high priority.

[3] It is known that aggregating wind power generation with transmission lines from multiple, geographically dispersed wind farms reduces the variability of their output [*Archer and Jacobson*, 2007]. The utility of connecting offshore wind farms along the East Coast was specifically explored by *Kempton et al.* [2010] using reanalysis data. That study found that wind farms located 1000 km apart and aligned along the prevailing movements of fronts would reduce ramp rates and lower the number of no and full-power events. Offshore grids to connect offshore wind energy (OWE) farms have been proposed in the European North Sea and off the US Mid-Atlantic. One such proposed offshore grid, called the *Atlantic Wind Connection*, would be located between Long Island, New York to Norfolk, Virginia.

[4] Ideally, the location of an offshore grid would maximize electricity generation during peak demand periods and utilize the synergistic effects of geographically distributed wind farms subject to different weather systems. Nearly all potential East Coast OWE locations are driven primarily by large, synoptic-scale weather systems passing every few days, with length scale on the order of 1000 km. Some offshore locations adjacent to the coast are subject to often strong and regularly occurring sea and land breezes, which occur on the mesoscale (few-100 km). These breezes are caused the daily differential heating and cooling between land and water. The difference in frequency between synopic-scale and mesoscale weather systems presents an opportunity to couple the two systems and generate OWE with potentially reduced variability.

[5] Today's offshore wind farms connect each single wind farm directly to shore. Here we consider the connection of a set of wind farms optimizing the meteorologically-determined combined power output. Offshore transmission along the distances analyzed here is likely to be high-voltage direct current (HVDC), as the electrical losses for AC cables over long distances indicate HVDC is favored for distances greater than 50-100 km [*Bresesti et al.*, 2007; *de Alegría et al.*, 2009] although the specific type of transmission is not specifically relevant to the meteorologically-driven analysis that is the focus of this article.

[6] This article identifies an ideal location for an offshore grid based on the overall and peak-time OWE resource in shallow waters ≤50 m depth. To demonstrate the grid's feasibility and utility, we propose 12 randomly located candidate wind farms located in strongest East Coast OWE resource. We then illustrate the feasibility and utility of building and connecting 4 of those 12 wind farms, chosen on the basis of their synergistic power generation properties, driven by the differing meteorology of the sites studied. Note that this is a more refined analysis than *Kempton et al.*

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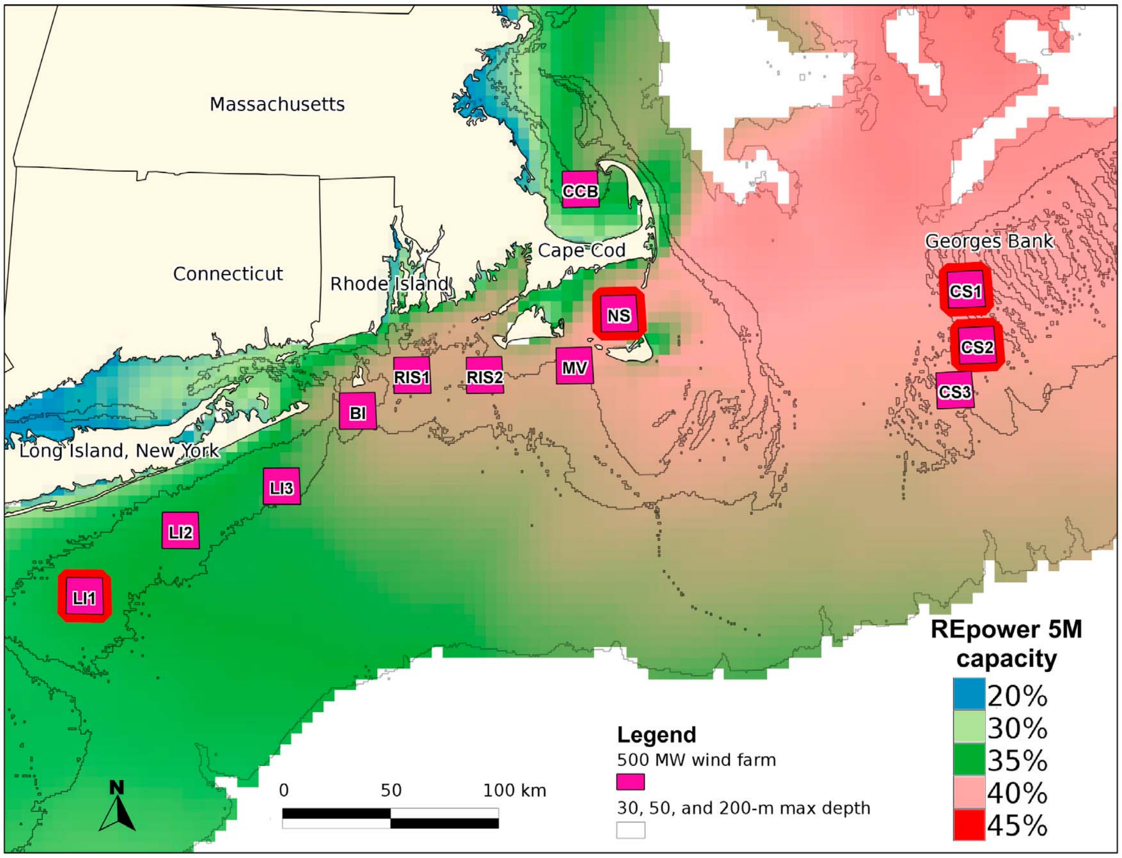

Figure 1. The 2006–2010, 90-m mean summer peak-time (08:00–21:00 EST) capacity factor (gross) based on a REpower 5M, 5.0-MW turbine. Twelve, 500-MW wind farms located in the highest capacity factor US East Coast summer peak-time wind resource and in waters $\leq$50-m depth are also shown. The four red-highlighted wind farms were selected for the ideal grid (*LI*1, *NS*, *CS*1, *and CS*2).

[2010] who found a substantial power leveling effect between OWE farms connected by long-distance transmission aligned along the movement of high and low pressure system. Here, rather than just aligning along the movement of weather systems, we use the characteristics of each site to pick a combination with a favorable combined power output. The aggregate offshore grid output is compared to individual output and characterized by hourly, seasonal, and interannual variability.

2. Methodology

[7] Our objective was to locate an “ideal” offshore grid with the following attributes:

[8] 1. highest East Coast overall and summer peak-time demand capacity factor

[9] 2. use bottom-mounted turbine foundations, which have been demonstrated in commercial use (water depth $\leq$ 50 m)

[10] 3. ability to connect to transmission regions from Boston to New York/New Jersey

[11] 4. combined wind farm output reduces seasonal and interannual variability and hourly ramp rates (i.e., the change in power over time from a generator, typically in $\mathrm{MW\ hr^{-1}}$)

[12] To locate the highest capacity factor overall and peak-time OWE resource, we used high-resolution mesoscale model data at the assumed turbine hub height of 90 m (M. J. Dvorak et al., US East Coast OWE resources and their relationship to peak-time electricity demand, submitted to *Wind Energy*, 2011, hereinafter D11) to calculate turbine capacity factors off the East Coast. The study used the Weather Research and Forecasting (WRF)-Advanced Research WRF (WRF-ARW) mesoscale weather model [*Skamarock et al.*, 2008] at high resolution $(5 \times 5\ \mathrm{km}^2)$, reinitialized every four days with the North American Regional Reanalysis (NARR). The WRF-ARW modeling domain, which spanned from Nova Scotia to South Carolina, used 14 surface buoys and 4 tall towers from the National Data Buoy Center for validation. A criterion to show modeling skill developed by *Pielke* [2002, p. 464] was used to validate the WRF-ARW model data hourly for the study years of 2006–2010. The WRF-ARW data met this criterion in the annual aggregate for all five study years.

[13] Besides an adequate OWE resource, depth is the major limiting economic and technological factor for the development of offshore wind turbines. Similar to *Lu et al.* [2009], *Dhanju et al.* [2008], and *Dvorak et al.* [2010], we choose bathymetry depth classes to classify approximately the current and future technological constrains that may be encountered when developing the offshore resource. A map of depth classes was created from a 30-arc second global bathymetry dataset [*British Oceanographic Data Centre*, 2009], with 30, 50, and 200-m depth contours, as shown in Figure 1. Monopile turbine foundations were assumed for waters $\leq$30 m, multi-leg foundations for waters $\leq$50 m, and floating turbines for the remaining waters out to $\leq$200 m.

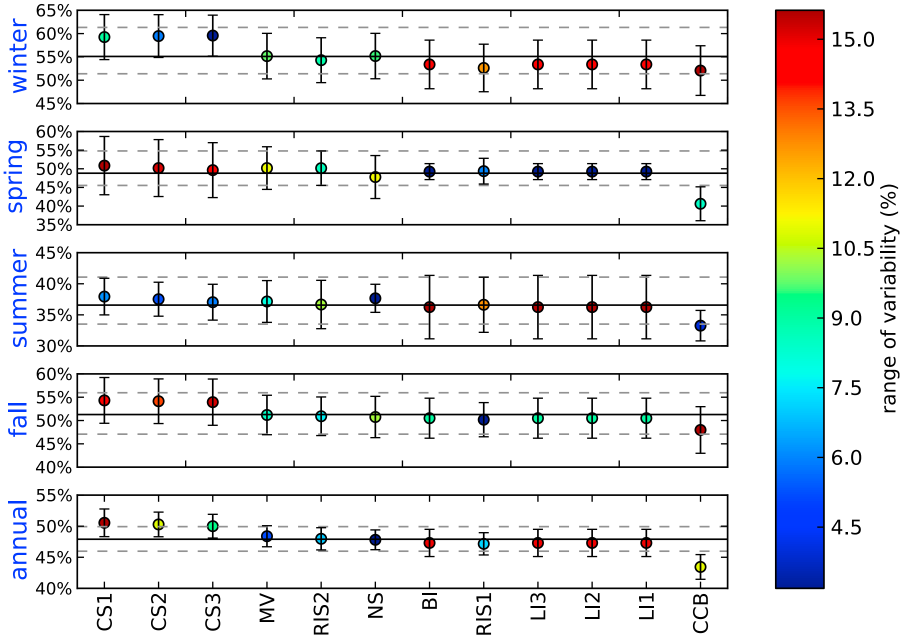

Figure 2. Peak-time (08:00–21:00 EST) seasonal and annual capacity factors (gross) for the 12 wind farms identified in Figure 1, sorted by annual capacity factor from left to right. Whiskers represent 5-year min and maxes based on 2006–2010 data, with the dot colors illustrating the range of interannual variability. The dark line represents the seasonal or annual mean, with dashed lines representing the mean min and max.

[14] D11 found the peak-time electricity demand to be from 08:00–21:00 EST along the entire East Coast coastal region, as well as the seasonal peak-time OWE resource at 90 m. The summer peak-time OWE resource is shown in Figure 1. Although a superior summer wind resource exists in the Gulf of Maine, that region has depths mostly >50 m. If we limit the water depths to likely near-term, non-floating turbine technologies, the study found the highest capacity factor peak-time summer resource in water ≤50 m is between Long Island, New York and the eastern side of Cape Cod, Massachusetts. The improved peak-time summer resource near the coast is primarily due to sea breezes that develop in this region [e.g., *Bornstein and Thompson*, 1981; *Bowers*, 2004; *Colby*, 2004; *Novak and Colle*, 2006]. *Colle and Novak* [2010] characterized a strong and larger-than sea breeze scale diurnal flow (100–200 km), called the *New York Bight Jet.* The jet develops most often during the spring and summer months in this region, and would improve the peak-time resource.

[15] The Boston-to-New York region identified above for the offshore grid is also optimal for two additional reasons. First, the most concentrated load on the East Coast exists in this region. Second, the severe hurricane risk is low or nearly non-existent in the region from Maine to Virginia. No Saffir-Simpson (SS) category 4 or 5 hurricanes have every hit this region from 1851–2006 and only 64 category 1–3 hurricanes have touched this same coastal area over the same period [*McAdie et al.*, 2006, p. 33], and current turbine design specifications [*Twidell and Gaetano*, 2009, p. 233] are not rated for winds greater than SS category 3.

3. Locating the Ideal Grid

[16] To demonstrate the feasibility and utility of an offshore grid, we propose 12 candidate 500 MW wind farms located based on wind resource and depth constraints previously outlined. Because competing ocean uses will exist and to reduce transmission network cost, we select the most ideal subset of four farms based on their synergistic properties.

3.1. Candidate Wind Farms

[17] A network of 12 500-MW wind farms were randomly located based on the first four criteria given in Section 2. Candidate wind farm locations are shown in Figure 1. Similar to *Dhanju et al.* [2008], *Pimenta et al.* [2008], *Lu et al.* [2009], *Dvorak et al.* [2010], and *Stoutenburg et al.* [2010], we chose a representative offshore wind turbine, to determine the hourly power generation at each farm. We placed REpower 5M, 5.0 MW turbines at $10D \times 10D$ spacing, where D is the rotor diameter of 126 m. The $10D \times 10D$ spacing is a conservative assumption and turbines could be placed closer together if the wind direction was predominately from one direction. Each 500-MW farm has a footprint of 12.6×12.6 km^2 or a turbine density of 3.2 MWkm^{-2}. The sizes, spacing, and locations chosen could be adjusted to suit economic, environmental, and policy constraints. The candidate farms were named according to geographic features in their proximity. From south-to-north in Figure 1: *Long Island* 1-3 (LI1-3), *Block Island* (BI), *Rhode Island Sound* 1-2 (RIS1-2), *Martha's Vineyard* (MV), *Nantucket Sound* (NS), *Cultivator Shoal* 1-3 (CS1-3), and *Cape Cod Bay* (CCB).

[18] To select an ideal subset of four wind farms that reduced hourly, seasonal, and interannual variability, several farm-to-farm metrics were analyzed. Peak-time (08:00–21:00 EST) seasonal and annual capacity factor are shown in Figure 2. Wind farms with high capacity factors, especially during the diminished summer resource, and with low interannual variability were considered most desirable.

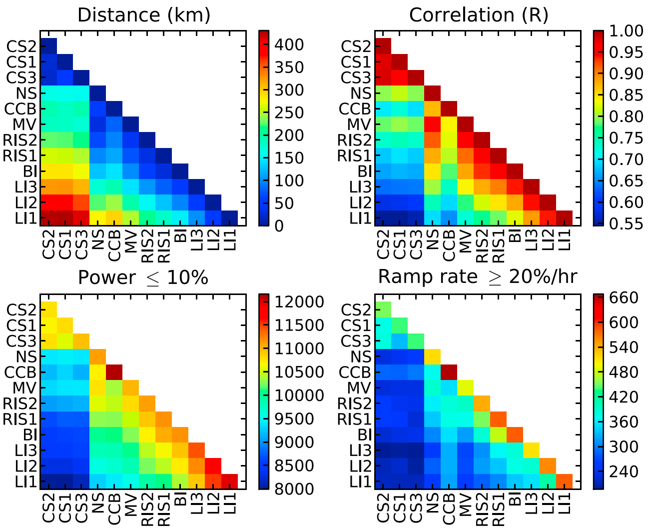

Figure 3. Comparative statistics for *pairs* of 500 MW farms identified in Figure 1 using modeled data for the 5 years of 2006–2010. Distance, hourly farm power correlation (R), number of times the power was below 100 MW, and number of times the hourly ramp rate exceeded 200 MW hr^{-1}. All power numbers are gross.

[19] While Figure 2 shows only individual farm attributes, it is important when designing a grid to choose wind farms that are compatible or have synergistic properties. Pairs of farms (i.e., 2 500-MW farms) were compared on the basis of distance apart, hourly power correlation, frequency of low power events, and frequency of high ramp up or down events (Figure 3). Pairs of farms that offered synergistic properties were selected for an ideal-grid farm subset.

[20] From the 12 candidate wind farms studied, a subset of 4 were selected to create a 2000 MW grid. CS1 was chosen for having the highest overall capacity factor and low interannual variability (see Figure 2). LI1 was chosen for its relationship to CS1. LI1 was the least correlated with CS1, had lowest number of high-hourly ramp rate events, and the fewest number of low wind power events (see Figure 3). LI1 also had remarkably low springtime interannual variability (Figure 2). NS had the second highest summer mean capacity factor (Figure 2) and exceptionally low interannual variability. Additionally, NS had low correlation with CS1 and CS2. Although CS2 had a similar wind profile to CS1, it has the second highest capacity factor and is uncorrelated with both NS and LI1. Although CCB is close to the load center of Boston, it had the lowest seasonal and annual capacity factor of all twelve farms, which accounts for much of its low correlation with other farms. It should be noted that other ideal combinations exist, but this specific combination thoroughly meets the offshore grid design objectives in Section 2.

4. Benefits of an Offshore Grid

[21] To determine if a constructive synthesis was obtained from the 4-farm ideal-grid, we analyzed several key statistics for improvement. We show that the offshore grid has fewer no-power events, smoother power output, and fewer hourly ramp rate extremes by connecting the four farms in a grid versus individual interconnection. Additionally, the capacity factor in the 4-wind farm subset was higher than for the 12-candidate farms.

4.1. Smoothed Generation Duration Curve

[22] The generation duration curve (GDC) in Figure 4 shows the percentage of a year that a wind farm operates at a given power output state, which is also the utilization of the offshore transmission line to transmit that power to shore. An interconnected transmission line with 4 farms transmits zero power about 4% of the hours in a year, whereas individually connected farms transmit zero power about 9% of the year. Interconnection yields a 5% reduction in the hours in a year that the transmission line operated at zero capacity. The 4-farm layout has a strong 48.4% (gross) 5-year capacity

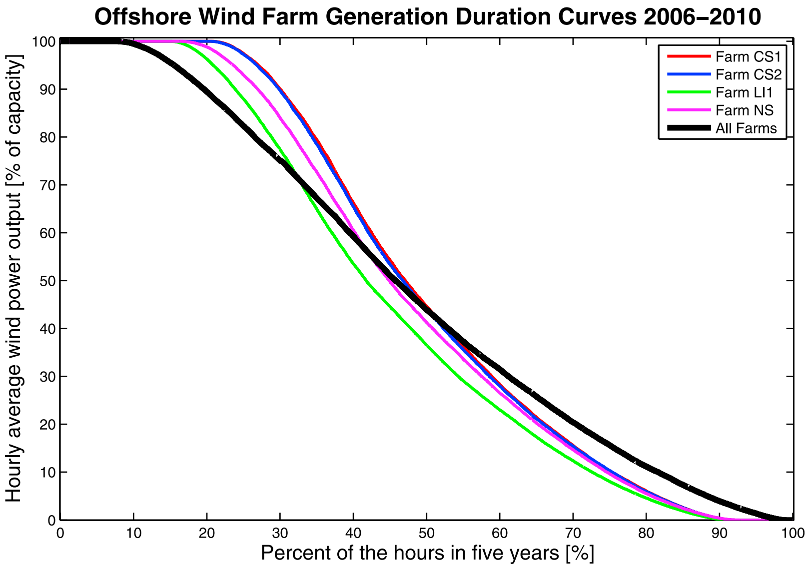

Figure 4. Generation duration curves, scaled by installed capacity for the 4 individual farms (500 MW) identified in Figure 1 and the combined 4-farm offshore grid (2000 MW) based on 2006–2010 hourly wind power data.

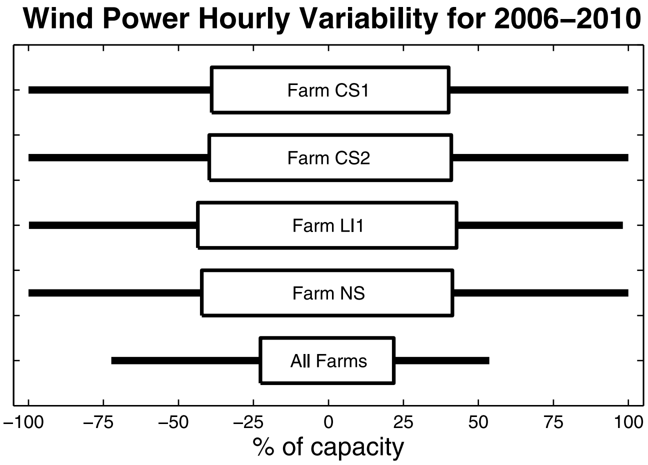

Figure 5. Hourly ramp rates, normalized by percent of installed capacity for the 4 individual farms (500 MW) identified in Figure 1 and for the combined offshore grid (2000 MW), based on 2006–2010 hourly wind power data. Boxes represent the 99th percentile of ramp up and ramp down events. Whiskers represent the most extreme 1% of ramp events in 5 years.

factor. The gross peak-time summer (Jul, Aug, Sep) and wintertime (Jan, Feb, Mar) capacity factor is 36.5% and 56.7% over the 5 years.

[23] The smoothed GDC of the four combined farms (Figure 4) indicates more consistent power output that is more conducive to matching load. An important second use of the transmission line would be to transfer power generated onshore along the subsea transmission line to the other onshore interconnections. Electricity on this transmission line could bypass the congested land based transmission system between the load centers of Boston and New York/New Jersey for reliability and price arbitrage.

[24] Long distance offshore transmission connecting wind farms in the prescribed manner might add about 5% to the cost of the entire assembly. Leveling power from current wind farms adds also approximately 3–5% to the cost of power, but that percentage may go up as a larger fraction of power comes from wind [*Kempton et al.*, 2010]. Therefore, transmission connecting wind farms would almost pay for itself in the value of leveling, with other transmission benefits, such as reliability, moving power to where it is more valuable, etc, justifying the cost of such a project.

4.2. Reduced Variability Through Aggregation

[25] As we plan for higher levels of penetration of renewables, a central challenge is managing the variability (i.e., the hourly ramp rate [MW hr^{-1}]) and uncertainty in their power output. One strategy to mitigate variability is to connect geographically diverse wind farms. This reduces the variability on several time scales, particularly the one-hour time scale relevant for power system operation and markets. Figure 5 compares the one-hour ramp rate as a percentage of capacity of the four individual wind farms and the four wind farms combined. The figure quantifies the one-hour change in power output between consecutive hours since these changes must be balanced by other generators in the system. The 99th percentile has been found to be an accurate predictor of ramp events that a utility should plan for [*Holttinen et al.*, 2008]. Figure 5 shows that four independent wind farms injecting highly variable wind power separately at four locations have more and larger ramps than do four combined farms.

[26] Specific grid injection points were not determined in this study. The layout proposed here connects the regional transmission grids of PJM (Mid-Atlantic), NYISO (New York state), and ISONE (New England) (Obj. 4 from Section 2). A survey of the onshore transmission systems along the East Coast shows that there are only a few places along the coast where high voltage lines required to move this level of power exist. Securing transmission easements to build new lines in a densely populated area would be challenging and expensive. Ideally, the onshore interconnection points would be near large load and generation centers more capable of managing the variability than single radial connections of four individual wind farms to various parts of the New England and Mid-Atlantic coastline.

5. Conclusion

[27] This paper identified the location of an "ideal" offshore wind energy (OWE) grid on the U.S. East Coast that would (1) provide the highest overall and peak-time summer capacity factor, (2) use bottom-mounted turbine foundations (depth ≤50 m), (3) connect regional transmissions grids from New England to the Mid-Atlantic, and (4) have a smoothed power output, reduced hourly ramp rates and hours of zero power. The grid would be located in the waters spanning from Long Island, New York to the Georges Bank, ≈150 km east of Cape Cod, Massachusetts.

[28] Twelve candidate 500 MW wind farms were located randomly throughout this region. We selected 4 wind farms (2000 MW total capacity) on the basis of their synergistic meteorological characteristics on varying length and temporal scales, to reduce the variability in the offshore grid. The combined grid size of 2000 MW, composed of 4 wind farms was somewhat arbitrary. The sizes and locations could be adjusted to suit economic, environmental, and policy constraints. Sites likely to have sea breezes (e.g., Long Island and Nantucket Sound) helped increase the peak-time capacity factor during the spring and summer months. Sites far offshore, dominated by powerful storms on the synoptic scale, were included for their generally higher but more variable power output (see the auxiliary material for additional data and discussion).[1] We showed these two distinct types of OWE resource had lower hourly power correlation and were complementary matches to reduce variability.

[29] The benefits of interconnection were analyzed by comparing the output of the four individual farms with their combined output. By selecting the two wind farms with the highest capacity factors (CS1 and CS2 on the Georges Bank), the overall offshore grid capacity factor remains high at 48% (gross). Including farms with exceptionally high capacity factors allowed the other two uncorrelated farms with lower capacity factors to be included, while still keeping the offshore grid capacity factor high. By interconnecting the farms via an offshore grid, the no-power events were reduced by 5%.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL050659.

[30] The location of this grid is ideal because ties together key attributes which create a powerful synergy. The abundance of shallow water in this region (≤50 m) makes development possible using existing turbine foundation technology. D11 found that the waters ≤50 m from Maine to Virginia could provide 19–43% of US East Coast electricity sales (about one-third of the US population). In comparison, California could only generate 17–31% of its electricity needs in its waters ≤50 m (about one-tenth of the US population) [*Dvorak et al.*, 2010]. The sea breeze (mesoscale flow) prevalent in the Connecticut, Rhode Island, and Massachusetts area is due in part to the additive effect of the summer position of the Bermuda-Azores High [*Colby*, 2004]. Locations farther down the East Coast (New Jersey through Virgina) are not oriented properly to take advantage of this additive effect. The powerful Nor'easters that roar through the region create a strong base-OWE resource in all but the summer months, where the sea breeze helps make up the difference.

[31] We have also shown that by interconnecting OWE farms ≈450 km apart in regions with OWE resources driven by synoptic-scale (1000 km length scale) and mesoscale (few-100 km) weather systems like sea breezes, substantial reductions in low/no-power hours and hourly ramp rates can be made. This is a complimentary result to *Kempton et al.* [2010] that found that farms separated by 1000 km reduces aggregate variability. Similarly, *Archer and Jacobson* [2007] looked at inland wind farms that were up to 850 km apart and found improved reliability for the aggregate array, but they did not include a correlation-based criterion. Here, sites were selected for interconnection based on their synergistic characteristics at the mesoscale. We find that this approach produces the valuable effects of leveling and hourly ramp rate reduction at a much smaller geographic scale.

[32] An offshore grid similar to the one proposed here has several distinct advantages. An offshore grid as an extension of the onshore grid will reduce transmission congestion along the densely populated US East Coast improving reliability and reducing power price differences between regions that the offshore grid connects. All the benefits of an offshore grid help to allocate its costs to more market actors than just the offshore wind farms, which improves the economics of adding renewable energy to the power system.

[33] **Acknowledgments.** MD and ES were supported by the Charles H. Leavell Graduate Fellowship and the US EPA (grant RD83337101O). WK was supported by the Otto Mønsted Foundation. The NASA Advanced Supercomputing (NAS) Division and NCAR Computational & Information Systems Laboratory (CISL) provided access to computational resources and global weather datasets, respectively, used in the mesoscale modeling.

[34] The Editor thanks Xi Lu and an anonymous reviewer for their assistance in evaluating this paper.

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