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SUPPLEMENTAL ONLINE MATERIAL: US East Coast offshore wind energy resources and their relationship to peak-time electricity demand

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S1. CLIMATOLOGY

S1.1. Wind fields

Reanalysis data were used to approximately determine the climatology of the wind fields during years modeled in the study, 2006-2010 (Section 4.2). The NCEP/NCAR Reanalysis Project (NNRP) produces 6-hourly 2.5 x 2.5 gridded data for atmospheric variables using a combined global data assimilation and forecasting system [1, 2]. Zonal and meridonial wind speed values from the surface layer (.995 sigma level) of 14 grid cells (shown in Figure S1) were analyzed from 1949-2010. Of these grid cells, 10 fell within in the *North* modeling domain and 8 in the *South*, which accounts for the overlap of the mesoscale modeling domains described in Section 4.1 (see Figure 1 for domain boundary definitions).

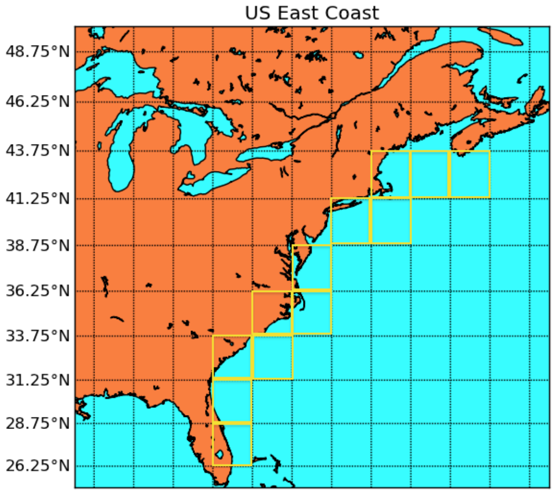
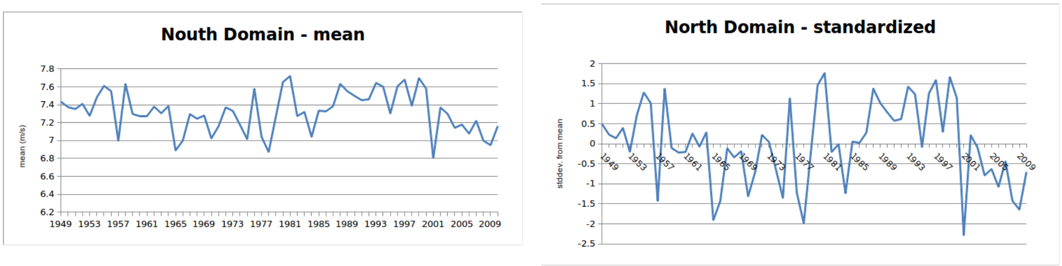


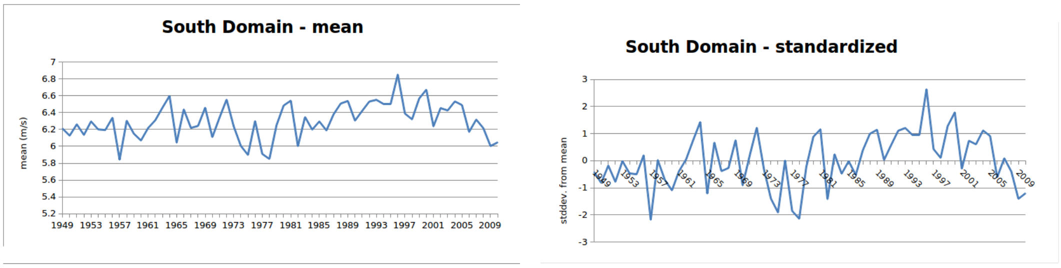
Figure S1. NNRP grid cells used to analyze the climatological mean.

Wind speeds for each 6-hour period were calculated as the magnitude of the vector sum of the zonal and meridonial scalar wind velocities. The annual mean wind speed in each grid cell was then calculated from the 6-hourly values. The grid cells of the North and South domains were then averaged to produce annual mean wind speed in each domain. The resulting annual data from 1949-2010 was then standardized in each domain as shown in Figure S2 and S3.



(a) Annual mean wind speed (ms^{-1}) (b) Annual standardized wind speed

Figure S2. North Domain climatological wind statistics from NNRP data for the years 1949-2010.

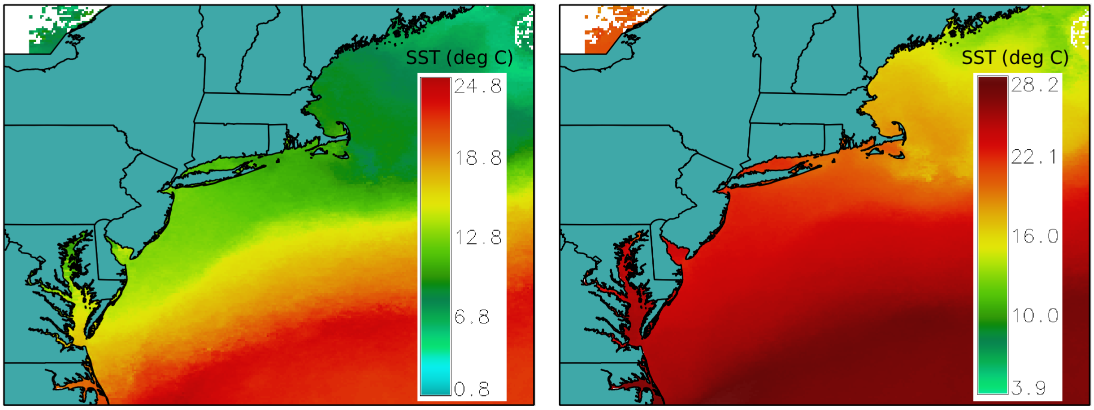


(a) Annual mean wind speed (ms^{-1}) (b) Annual standardized wind speed

Figure S3. South Domain climatological wind statistics from NNRP data for the years 1949-2010.

S1.2. Sea surface temperatures

Mean sea surface temperatures (SST) derived from 4-km resolution NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite data from 1985-2001 [3], shown in Figure S4 and S5.



(a) Spring (AMK) SST (b) Summer (JAS) SST

Figure S4. Mean SST, 1985-2001 from Virginia-to-Maine [3].

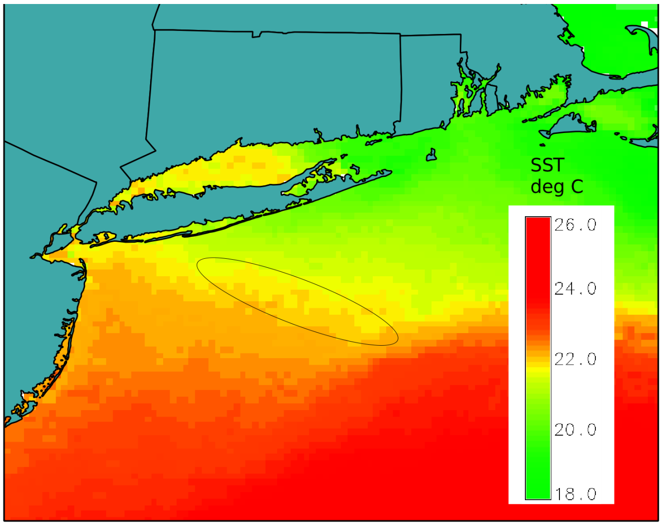


Figure S5. Mean summer SST in the vicinity of *Block Canyon*, denoted by the black ellipse [3].

S2. VALIDATION OF MESOSCALE MODELED WINDS

S2.1. Calculation of unbiased RMSE

The third criteria, the unbiased RMSE, used for model validation is described in [4, p. 464]. The unbiased wind speed RMSE was calculated by using the bias calculated for each buoy group by the buoy and month, as well as the closest WRF-ARW modeling grid point. The RMSE is then recalculated by subtracting the bias from each WRF wind speed at each hour.

S2.2. Wind fields used for offshore tower validation

Due to disk space limitations, it is only feasible to store the WRF-ARW wind speeds at a few discrete heights in the lower planetary boundary layer. Offshore tower data (see Section S2.4 for towers and measurement height) was compared to WRF-ARW winds at the 45 m height. The lowest (tallest) tower used was 16 m (50 m). Wind shear in a neutrally boundary becomes less pronounced as height above ground level increases. Using the log-low for vertical scaling of wind speed (Equation S1) and surface roughness of $z_o = 0.20x10^{-3}m$ [5], the difference in wind speed going from the 16-to-45-m and 45-to-50-m height is 9.2% and $< 0.1\%$.

$$s(z_2)/s(z_1) = ln\left(\frac{z_2}{z_o}\right)/ln\left(\frac{z_1}{z_o}\right) \tag{S1}$$

To additionally illustrate this point, we calculated the RMSE and bias of the largest difference in validation height for the entire year of 2010 for the MLRF1 tower, from 16 to 45 m with and without the log-law scaling. Results are shown in Table SI. By adding in the log-law assumption, both the RMSE and bias are increased significantly.

Table SI. Validation statistics for the Molasses Reef, FL (MLRF1) tower, with anemometer height of 16 m compared to the WRF 45 m data, with and without a log-law scaling factor of $1.11 * v_{buoy}$.

	WRF avg (ms^{-1})	**MRLF1 avg** (ms^{-1})	**RMSE** (ms^{-1})	**bias** (ms^{-1})	**WRF stddev** (ms^{-1})	**MRLF1 std-dev** (ms^{-1})
log-law ($v_{buoy} * 1.11$)	6.16	7.11	2.60	-0.95	2.73	3.17
no log-law	6.16	6.42	2.28	-0.27	2.73	2.87

S2.3. Buoys

List of National Data Buoy Center buoys used for validation in 4.3 (see Figure 1 for a map of buoy locations):

- Station 44034 - Buoy 44034 (I0124) - Eastern Maine Shelf, 44.106 N 68.109 W 5 m height (GoMOOS)

- Station 44005 - Gulf of Maine 78 nm E of Portsmouth, NH, 43.189 N 69.140 W 5 m height
- Station 44007 (LLNR 75) - PORTLAND 12 NM Southeast of Portland,ME, 43.531 N 70.144 W 5 m height
- Station IOSN3 - Isle of Shoals, NH, 42.967 N 70.623 W 5 m height
- Station 44013 (LLNR 420) - BOSTON 16 NM East of Boston, MA, 42.346 N 70.651 W 5 m height
- Station 44018 (LLNR 560) - SE Cape Cod 30NM East of Nantucket, MA, 41.255 N 69.305 W, 5 m height (CWIND) (Since 2002)
- Station 44011 (LLNR 825) - GEORGES BANK 170 NM East of Hyannis, MA, 41.118 N 66.578 W - 5 m height
- Station 44008 (LLNR 580) - NANTUCKET 54NM Southeast of Nantucket, 40.502 N 69.247 W 5 m height
- Station 44017 (LLNR 665) - 23 Nautical Miles Southwest of Montauk Point, NY, 40.692 N 72.048 W, 5 m height
- Station 44025 (LLNR 830) - LONG ISLAND 33 NM South of Islip, NY, 40.250 N 73.166 W 5 m height
- Station 44009 (LLNR 168) - DELAWARE BAY 26 NM Southeast of Cape May, NJ, 38.464 N 74.702 W 5 m height (CWIND)
- Station 44014 (LLNR 550) - VIRGINIA BEACH 64 NM East of Virginia Beach, VA, 36.611 N 74.836 W, 5 m height (CWIND)
- Station 44004 (LLNR 5) - HOTEL 200NM East of Cape May,NJ, 38.484 N 70.433 W, 5 m height
- Station DSLN7 - Diamond Shls Lt., NC, 35.153 N 75.297 W, 5 m height (CWIND) (1984-2003)
- Station 41025 (LLNR 640) - Diamond Shoals, 35.006 N 75.402 W, 5 m height (CWIND) (2003-present)
- Station 41001 (LLNR 635) - 150 NM East of Cape HATTERAS, 34.675 N 72.698 W, 5 m height (CWIND) (died June 2008-April 2010)
- Station 41004 (LLNR 825) - EDISTO - 41 NM Southeast of Charleston, SC, 32.501 N 79.099 W, 5 m height (CWIND)
- Station 41002 (LLNR 830) - S HATTERAS - 250 NM East of Charleston, SC, 32.309 N 75.483 W, 5 m height (CWIND) (Missing 2009/2010)
- Station 41012 (LLNR 845.3) - St. Augustine, FL 40NM ENE of St Augustine, FL, 30.041 N 80.533 W, 5 m height (Started 2002)
- Station 41008 (LLNR 833) - GRAYS REEF - 40 NM Southeast of Savannah, GA, 31.402 N 80.869 W, 5 m height (CWIND)
- Station 41009 (LLNR 840) - CANAVERAL 20 NM East of Cape Canaveral, FL, 28.519 N 80.166 W, 5 m height
- Station 41010 (LLNR 845) - CANAVERAL EAST 120NM East of Cape Canaveral, 28.906 N 78.471 W, 5 m height
- Station 41036 (LLNR 802) - Onslow Bay Outer, NC, 34.206 N 76.952 W, 5 m height (2006-07 to present)
- Station 41013 (LLNR 815) - Frying Pan Shoals, NC Buoy, 33.436 N 77.743 W, 5 m height (2003-11 to present)

S2.4. Offshore Towers

List of National Data Buoy Center offshore towers used for validation in Section 4.3 (see Figure 1 for a map of offshore tower locations):

- Station CHLV2 - Chesapeake Light, VA, 36.910 N 75.710 W - 43.3 m above site elevation
- Station FWYF1 - Fowey Rocks, FL, 25.590 N 80.097 W - 43.9 m above site elevation
- Station SKMG1 - U.S. Navy Tower M2R6 GA, 31.534 N 80.236 W 50.0 m above site elevation
- Station TYBG1 - U.S. Navy Tower R8 GA, 31.633 N 79.925 W 32.0 m above site elevation
- Station SPAG1 - U.S. Navy Tower R2 GA, 31.375 N 80.567 W - 50 m above site elevation
- Station MISM1 - Matinicus Rock, ME, 43.783 N 68.855 W 22.9 m above site elevation
- Station MDRM1 - Mt Desert Rock, ME, 43.968 N 68.128 W 22.6 m above site elevation
- Station MLRF1 - Molasses Reef, FL, 25.010 N 80.380 W 15.8 m about site elevation (CWIND)
- Station SMKF1 - Sombrero Key, FL, 24.627 N 81.110 W 48.5 m above site elevation (CWIND)

S3. PEAK-TIME ELECTRICITY USE

This section describes the data and methods used to determine the peak-time electric use for the USEC in Section 5.2. The first section covers the analysis of the diurnal peak from real load data. The second section compares and contrasts our general conclusion that peak-time is from 08:00-21:00 EST to real utility peak-time definitions.

S3.1. Daily peak-time calculation

Five FERC regions border the coastal region of interest; 1) ISO-New England serving all of New England (Maine through Connecticut), 2) New York Independent System Operator (ISO) serving New York, 3) PJM Interconnection serving Maryland, Delaware, and Virginia, 4) Southeastern Electric Reliability Council (SERC), and 5) Florida Reliability Coordinating Council (FRCC).

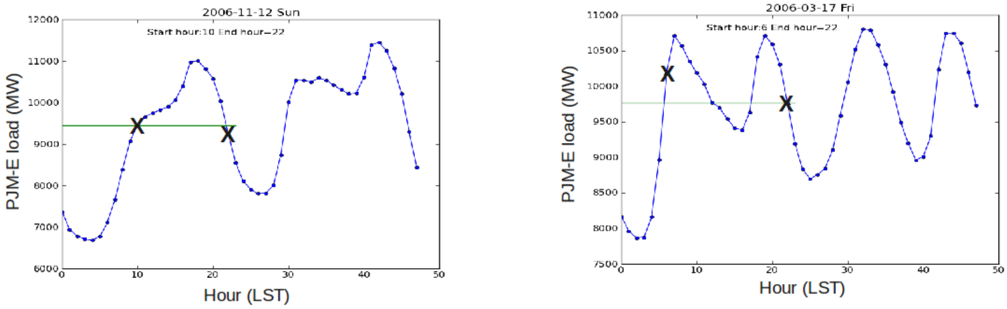
SERC Coastal, hereafter SERC-C includes SERC entities primarily in North Carolina, South Carolina, and Georgia that do not overlap with PJM (specifically, the PJM Dominion zone). This overlap in regions is caused by the fact that SERC is a NERC region, while PJM is a FERC region. SERC and FERC consist of different and often overlapping boundaries. FRCC includes all entities in the FRCC NERC region (all of Florida except west of the Apalachicola River on the panhandle). The exact regions used in the analysis for the SERC-C and the FRCC are listed in Tables II(a) and II(b), respectively.

Load data was available from both independent system operators (ISOs) and from Federal Energy Regulator Commission (FERC) survey. Hourly load data was downloaded for the years 2006-2010 for the ISO-New England (ISO-NE) [6], the New York ISO (NYISO) [7], and the PJM Interconnection [8]. FRCC and SERC-C hourly load data were downloaded by entity from FERCs form 714 data download and viewer softwares for 2006-2009. 2010 data was not available at the time of analysis, as balancing areas/utilities are not required to submit their 2010 data until June 1, 2011.

A computer program was written to automatically identify the start and end of the daily peak. We defined the *peak demand period* as the time period starting when an increasing load first goes above the daily median and the last time load is decreasing goes below the median. Because this median value sometimes occurs in the early morning of the next day, it was necessary to analyze 48 hours of load data at a time, despite the fact that we were interested in only the first 24 hours of data. Because load serving entities report the demand at the end of each hour for the previous hour, it was assumed that the demand stated was the same for the entire preceding hour (e.g. a demand reported at 13:00 was assumed to be the demand from 12:00-12:59).

The general algorithm proceeds as follows:

1. Retrieve 48 hours of load data for a given ISO/RTO region.
2. Find the extremes for the first day: *daily maximum* and *first morning minimum*. Find the next load minimum, which often occurs the following day.
3. Find the median for that minimum-to-next-daily-minimum period.
4. Find the first time the load is closest to the median, starting at the *first morning minimum*. Make sure the load is increasing when it crosses the median. Pick the closest hour to where the load crosses the *daily median*.
5. Find the last time the load is closest to the *daily median*, starting at the next occurring *daily minimum* and iterating backwards in time.



(a) PJM-E load for 2006-11-12 through 2006-11-13 (EST)

(b) PJM-E load for 2006-03-17 through 2006-03-18 (EST)

Figure S6. Example load analysis to determine start and end times of the daily median load, denoted by the green-horizontal line. 'X' marks the start and end hours chosen.

This method in general worked well to characterize the start and end time of the median of daily load. Because the shape of the load is not always a perfect monotonically increasing time series to the peak and decreasing after the peak, this method in general found reasonable peak start and end times for nearly every day of the year. Examples are shown in Figure S6 of where median load starts and stops, including an example of days with a single peak (Figure 6(a)) and double peak (Figure 6(b)).

Some datasets from FERC did not adequately account for the extra hour value at the end of daylights savings. In these cases, we created a representative value for this extra hour using nearby data in the set.

Table SII. Utilities included in the peak-time analysis for SERC-C and FRCC.

(a) SERC-C

Balancing Area, Planning Area, or Utility Name	Abbreviation	Year(s) Used	Note
Alcoa Power Generating Inc.	YAD	2006	
Alcoa Power Generating Inc.	YAD	2007-2009	Data set was empty (all 0s).
City of Conway	CNWY	2006-2008	Data set was empty (all 0s).
City of Conway		2009	Data set was empty (all 0s). Negative load values, indicating net power import.
Duke Energy Carolinas, LLC	DUK	2006-2009	
Georgia Power Company		2006-2009	
Oglethorpe Power Company		2006-2009	
Progress Energy (Carolina Power & Light Company)	CPLE, CPLW	2006-2009	
South Carolina Electric & Gas	SCEG	2006-2009	
South Carolina Public Service Authority	SC	2006-2009	
Southeastern Power Administration Hartwell	SEHA		Not listed in FERC Form 714 software.
Southeastern Power Administration Russell	SERU		Not listed in FERC Form 714 software.
Southeastern Power Administration Thurmond	SETH		Not listed in FERC Form 714 software.
Southern Power Company		2006-2009	

(b) FRCC

Balancing Area, Planning Area, or Utility Name	Abbreviation	Year(s) Used	Note
City of Homestead	HST	2006-2009	Data set was empty (all 0s).
City of Tallahassee	TAL	2006-2009	
Florida Municipal Power Agency		2006-2009	
Florida Municipal Power Pool	FMPP	2006-2009	Data set was empty (all 0s).
Florida Power and Light Company	FPL	2006-2009	
Gainesville Regional Utilities	GVL	2006-2009	
JEA (Jacksonville)	JEA	2006-2009	
Lakeland Electric		2006-2009	
Orlando Utilities Commission		2006-2009	
Progress Energy (Florida Power Corporation)	FPC	2006-2009	
Reedy Creek Improvement District	RC	2006-2009	Data set was empty (all 0s).
Seminole Electric Cooperative, Inc.	SEC	2006-2009	
Tampa Electric Company	TEC	2006-2009	

S3.2. Peak-time defined compared to utility peak definitions

The time-of-use rate plans available through utilities in the EC region define on-peak hours for a variety of durations, frequencies, start and end hours, seasonal differences, and customers (residential and/or commercial). For example, Delmarva Power, a utility company serving Delaware and the eastern coast of Maryland, defines on-peak hours during weekdays and holidays year-round from 08:00 to 21:00 EST in Delaware (PJM-E region) [9, p. 58] and 09:00 to 20:00 EST in Maryland (PJM-DOM region) [10, p. 63]. Georgia Power, a utility company in the SERC-C region, recognizes a much shorter and seasonally-based on-peak period, from 13:00 to 18:00 EST during weekdays excluding holidays from June to September [11].

Other utilities, particularly those in the more southern areas of the USEC extent, have different peak hour definitions for different times of the year. For instance, Duke Energy Carolinas, the portion of the Duke Energy power company serving North and South Carolinas (SERC-C region), classifies on-peak hours as weekdays from 12:00 to 20:00 EST during June to September and 06:00 to 13:00 local prevailing time during October to May [12]. In addition to different seasonal definitions for peak periods, Florida Power and Light Company [13, p. 2] and Progress Energy Florida [14, p. 2], two utilities in the FRCC region, have multiple daily peaks. These two utilities characterize on-peaks hours as weekdays excluding holidays from 06:00 to 10:00 and 18:00 to 22:00 local prevailing time during November to March and 12:00 to 21:00 local prevailing time during April to October, respectively. The twice-daily peak during the wintertime months reflect the double peak load profile due to electric heating loads, which peak in the evenings and mornings. In the summer, the single peak reflects daytime air conditioning loads.

S4. TURBINE POWER CURVE

The wind turbine power from a REpower 5M 5.0 MW offshore wind turbine was derived using a product brochure [15]. The power curve was digitized using the open source software *Plot Digitizer*. The power curve was split was piecewise defined from $[0 - 3.5\,\mathrm{ms}^{-1}), [3.5 - 9.14\,\mathrm{ms}^{-1}), [9.14 - 13.0\,\mathrm{ms}^{-1}), [13.0 - 30.0\,\mathrm{ms}^{-1}], and[30\,\mathrm{ms}^{-1}, \infty)$ to allow for a better fit of the polynomial. The details of the polynomial can be extracted from Figure S7.

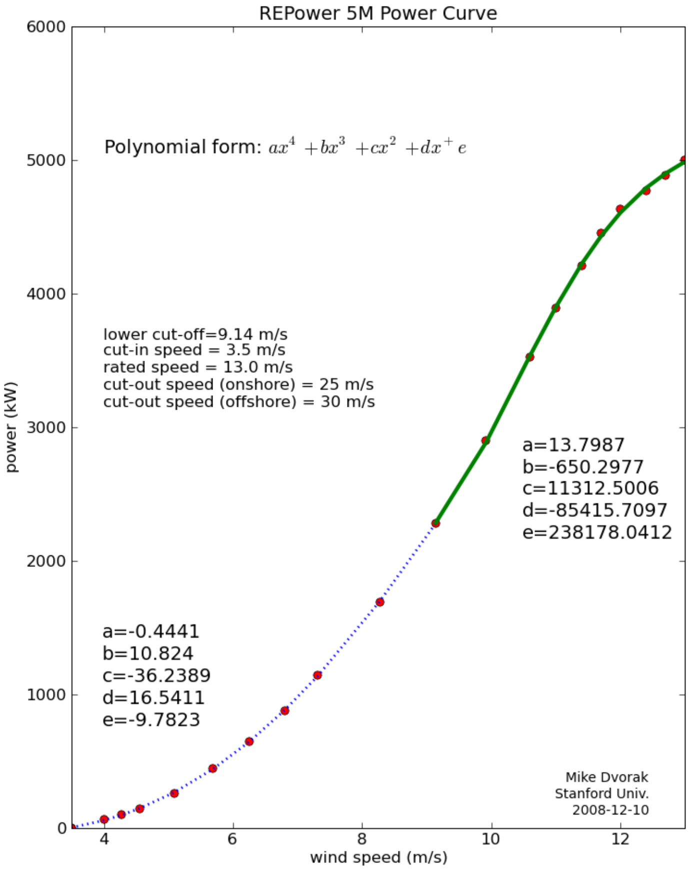
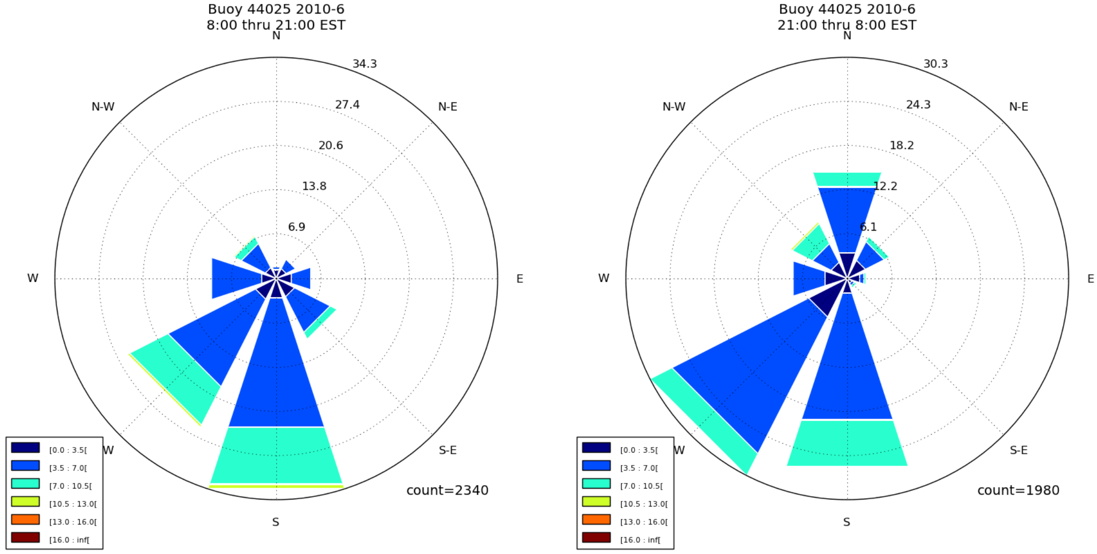


Figure S7. Digitized REpower 5M power curve.

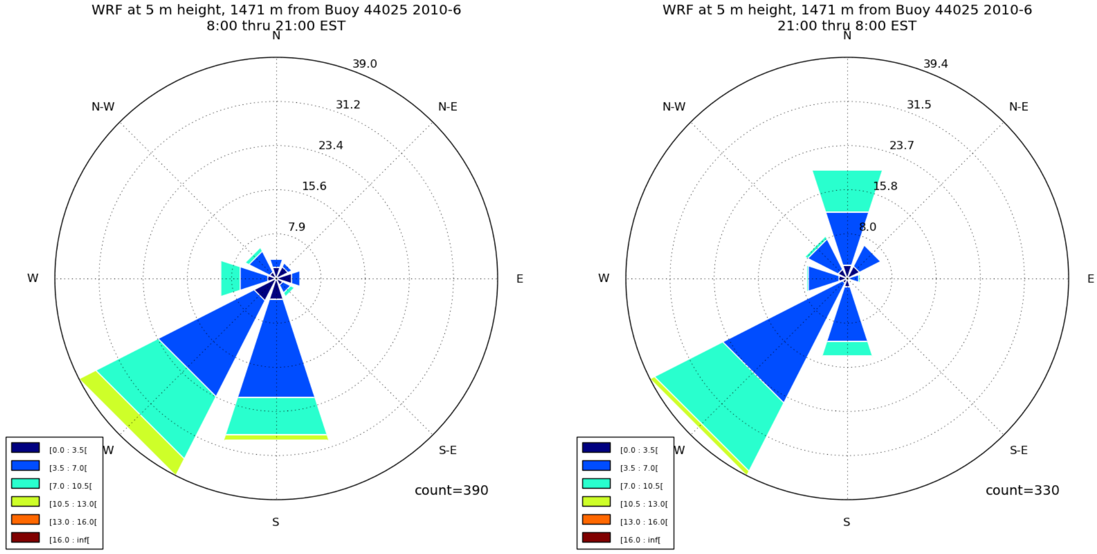
S5. SEA BREEZE OFF LONG ISLAND, NEW YORK



(a) Wind rose, 08:00–21:00 EST.

(b) Wind rose, 21:00–08:00 EST.

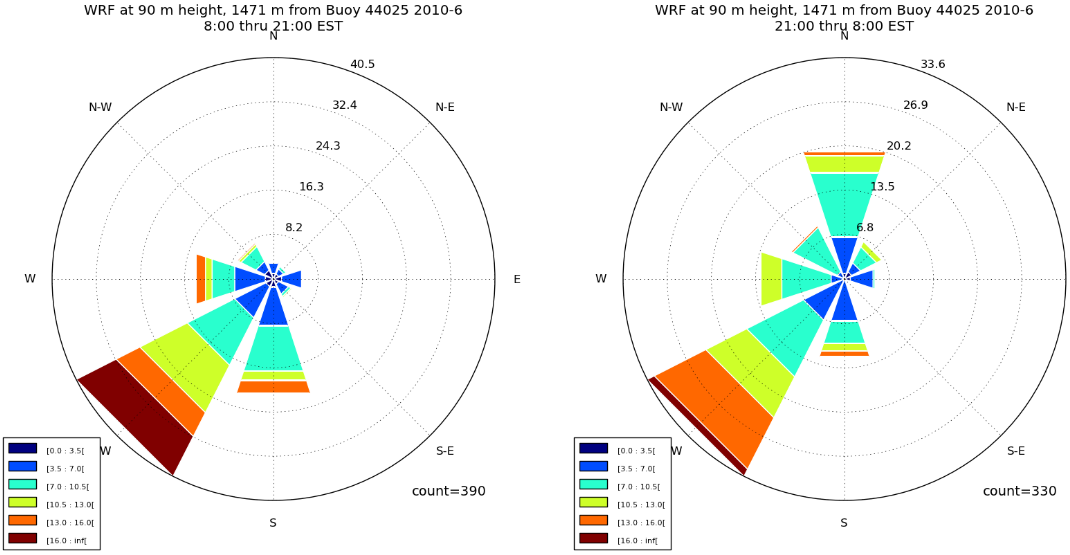
Figure S8. Wind roses for NDBC buoy 44025 (5 m height), 38 km off Long Island, New York for the month of June 2010. Rings are in percent and wind speed is in ms^{-1}.



(a) Wind rose, 08:00–21:00 EST.

(b) Wind rose, 21:00–08:00 EST.

Figure S9. Wind roses for 5 m height WRF-ARW model data near NDBC buoy 44025, 38 km off Long Island, New York for the month of June 2010. Rings are in percent and wind speed is in ms^{-1}.



(a) Wind rose, 08:00–21:00 EST.

(b) Wind rose, 21:00–08:00 EST.

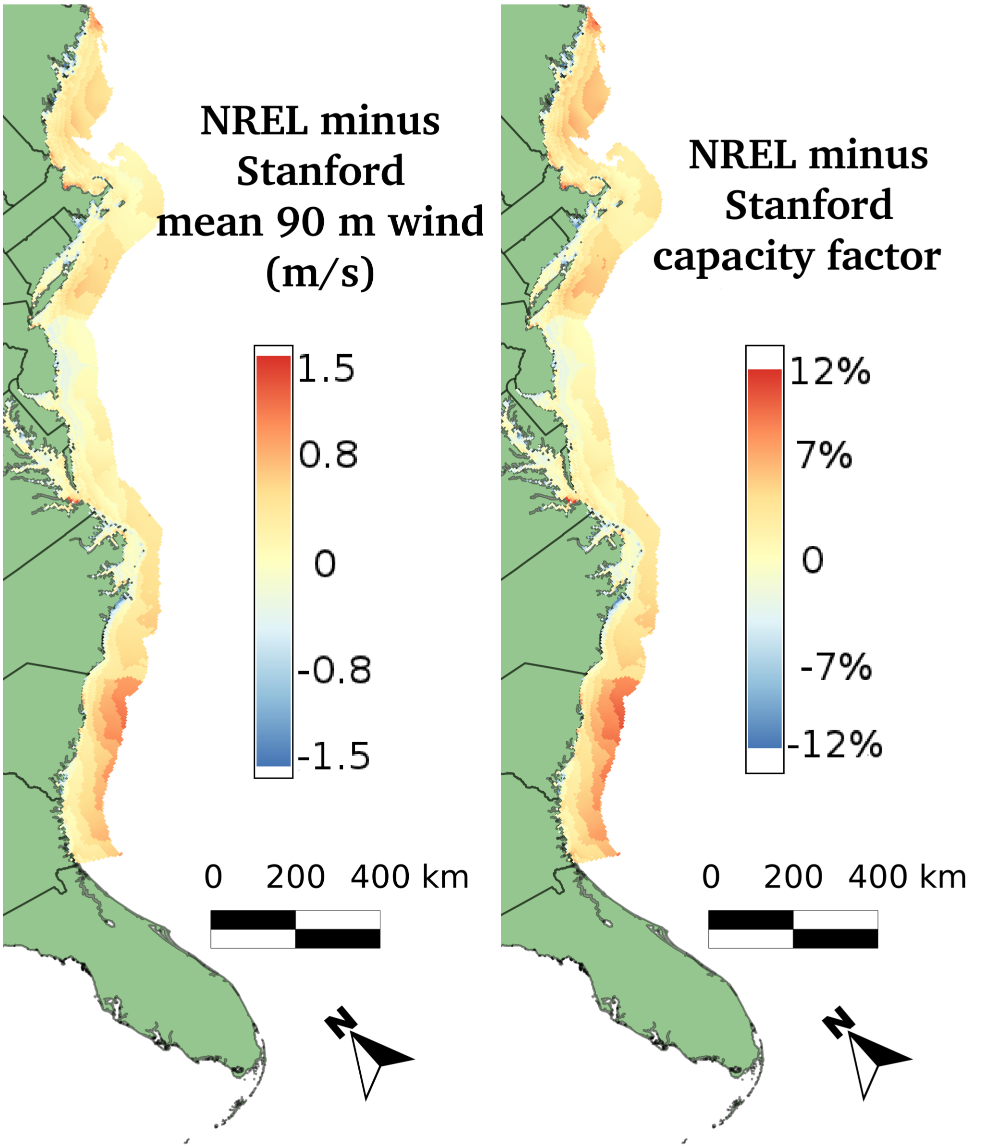
Figure S10. Wind roses for 90 m height WRF-ARW model data near NDBC buoy 44025, 38 km off Long Island, New York for the month of June 2010. Rings are in percent and wind speed is in ms^{-1}.

S6. COMPARISON TO NREL WIND MAPS

A high-resolution National Renewable Energy Laboratory (NREL) 90-m offshore wind map for the Atlantic was downloaded from the NREL GIS website [16] and loaded into GRASS GIS. The NREL map was reprojected to the projection of the WRF-ARW data (Lambert conformal conic) and turned into a 5.0x5.0-km raster layer, the same resolution for the WRF-ARW derived wind fields. A difference of the NREL minus the study mean wind speed is shown in Figure S11.

$$CF = 0.087\bar{v} - \frac{P}{D^2} \tag{S2}$$

The CF_{gross} field for the NREL maps was created with the empirical method developed by Masters [17], Equation S2. The NREL mean wind speed was used for $\bar{v}$ in ms^{-1} and the REpower 5M turbine power of 5000 kW was used for P and the diameter of 126 m used for D. A difference of the NREL extrapolated CF_{gross} minus the study hourly-integrated CF_{gross}, calculated from the five study years (same as Figure 3(c)) is shown in Figure S11.



(a) NREL minus Stanford 90 m mean wind speed.

(b) NREL derived CF_{gross} minus Stanford REpower 5M 90 m CF_{gross}.

Figure S11. Difference maps of NREL minus Stanford wind fields.

REFERENCES

1. Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, *et al.*. The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.* Mar 1996; **77**(3):437–471. URL `http://dx.doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2`.
2. Kistler R, Collins W, Saha S, White G, Woollen J, Kalnay E, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, *et al.*. The NCEP-NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.* Feb 2001; **82**(2):247–267. URL `http://dx.doi.org/10.1175/1520-0477(2001)082<0247:TNNYRM>2.3.CO;2`.
3. Casey KS, Kearns EJ, Halliwell V, Evans R. Seasonal sea surface temperature averages, 1985-2001 2004. URL `http://nationalatlas.gov/mld/sstalli.html`, accessed on 2011-09-26.
4. Pielke Sr RA. *Mesoscale meteorlogical modeling*. Academic Press: San Diego, 2002.

5. Manwell JF, McGowan JG, Rogers AL. *Wind energy explained : theory, design and application*. 2 edn., Wiley: Chichester, West Sussex, U.K., 2009.
6. ISO-NE. ISO New England - hourly zonal information 2011. URL http://www.iso-ne.com/markets/hstdata/znl_info/hourly/index.html, accessed on 2011-05-20.
7. NYISO. Real time actual load 2011. URL http://mis.nyiso.com/public/P-58Blist.htm, accessed on 2011-05-06.
8. PJM. PJM - hourly load data 2011. URL http://www.pjm.com/markets-and-operations/energy/real-time/loadhryr.aspx, accessed on 2011-05-01.
9. Delmarva Power. Delaware electric tariff. URL http://www.delmarva.com/_res/documents/DEMasterTariff.pdf, accessed on 2011-06-09.
10. Delmarva Power. Maryland electric tariff. URL http://www.delmarva.com/_res/documents/DPLMdMasterTariff.pdf, accessed on 2011-06-09.
11. Georgia Power. Glossary: On-peak. URL http://www.georgiapower.com/pricing/glossary.asp#onpeak.
12. Duke Energy. Rates: Time of use rates. URL http://www.considerthecarolinas.com/rates.asp.
13. Florida Power and Light Company. Rate schedules. URL http://www.fpl.com/rates/pdf/electric_tariff_section8.pdf.
14. Progress Energy Florida. Commercial/industrial rate schedules. URL https://www.progress-energy.com/assets/www/docs/company/PEFcommercialrateinsert.pdf.
15. REpower Sytems AG. REpower Systems AG: 5M goes offshore: the countdown is running. *Technical Report 2007*. URL http://www.repower.de/index.php?id=369&L=1.
16. NREL. Atlantic Coast 90m windspeed offshore wind high resolution. GIS Shp file Aug 2010. URL http://www.nrel.gov/gis/data_wind.html, accessed on 2011-08-05.
17. Masters GM. *Renewable and efficient electric power systems*. John Wiley & Sons: Hoboken, NJ, 2004.