Supporting Information

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SI Text

Wind Data. We draw wind observations from the National Data Buoy Center (NDBC) program (1), maintained by the National Oceanic and Atmospheric Administration (NOAA). We selected eleven stations, covering from Florida around 24°N latitude (station S1) to Maine at 43°N (station S11) (Fig. 1 in article), a total distance of about 2,500 km. Station selection is based on their nearly equal spacing and relatively low amount of missing data.

Seven of the stations are fixed platforms, lighthouses or towers mounted over water, while the others are moored meteorological buoys (either a 3-m discus buoy or a 6-m nomad buoy) illustrated in inserts to Fig. 1.

Anemometers on buoys are commonly located at $z_{\mathrm{ref}} = 5$ m above the sea level, towers are typically around $z_{\mathrm{ref}} = 40$ m. Their locations and characteristics are summarized in Table S1. The dataset has hourly time resolution, but each wind speed measurement represents an average of individual samples taken every second. The period for averaging these samples is 2 min for towers and 8 min for buoys (2).

To analyze concurrent winds, we selected only hours for which all 11 stations were working and had valid data. Specifically, using 5 yr of data from Jan 1, 1998, through Dec 31, 2002, we excluded large gaps ($\Delta t \geq 4$ h) and synchronized the times of different stations. Linear time interpolation filled gaps of less than 4 h. The resulting data base, used here, includes only 59% of the hours, but in each of those hours, data is present for all 11 stations. The data that did not satisfy our stringent criteria typically occur in periods of 2–4 wk; in addition, there is a large gap at the end of the time series. The remaining data employed in our analysis are fairly evenly distributed in time, with the months of January and July being slightly less well represented than the other months.

Extrapolation to Wind Speeds at Turbine Hub Heights. From the varying measurement reference heights, we extrapolated the wind speed to the hub-height of modern offshore wind turbines. Our extrapolation applied the log-law, assuming neutral stability of the atmosphere and a surface roughness length of $z_0 = 0.2$ mm, which is recommended as an average value for calm and open seas (3, 4) [for a derivation of a z_0 that varies with time and location, see Garvine and Kempton (5)]

$$V = V_{\mathrm{ref}} \frac{\ln(z/z_0)}{\ln(z_{\mathrm{ref}}/z_0)}. \quad [1]$$

Here V_{ref} represents the hourly average wind speed measured by the offshore meteorological station at the anemometer height z_{ref}. For z, the turbine hub-height, we use $z = 90$ m.

As an illustration of the scaled wind speed data resulting from the above-derived adjustments, Fig. S1 compares the wind speed at four dispersed stations, during two months for which there are no data gaps (May and November of 1999). The wind speed varies with both time and with the stations' geographical position. Line colors in Fig. S1 correspond to station colors in Fig. 1. These graphs suggest that wind regimes become more dissimilar with increasing distance among the stations. For instance, the time series for stations S8 and S10 bear some resemblance, but not those for S2 and S10. This is important for electricity generation, and is more systematically analyzed in the main article using correlation coefficients. We will describe translation of the wind speed into practical measures of power, and then detail the analysis of how the power generation varies geographically and with time.

Turbine Power Output. We estimate the electrical power output of an offshore turbine at each selected station with wind speed measurements. This is therefore an analog of placing a single wind generator at each location where there is now a met station. Practical commercial offshore wind developments would use a minimum of 100 turbines at each location, but our use of one turbine per location suffices to illustrate the patterns of fluctuation in electrical output across sites, a simplification used by other analysts (6, 7).

In order to calculate realistic turbine electric output from wind speed, we selected a 5 MW turbine type currently used offshore. However, the sensitivity of our analysis to turbine type is only a few percent (8). The reference turbine is the Repower 5 M, a 5 MW turbine from REpower Systems AG, shown in Fig. S2*B*. Its design follows the nearly universal contemporary configuration of a three-blade, horizontal axis turbine, with active-yaw to keep the blade upwind. The reference turbine has rotor diameter of 126 m and swept area of 12,469 m^2. Oceanic turbines have been mounted on tubular steel monopiles to 30-m depth, or on lattice leg structure for deeper waters, the latter shown in Fig. S2*B*.

The REpower 5 M's cut-in speed, below which it does not produce power, is 3.5 m s^{-1}. The maximum electricity generation, or rated power, is at wind speeds above 13 m s^{-1}. For self-protection, the REpower 5 M automatically shuts off at winds stronger than 30 m s^{-1}. These characteristics can be seen in its power curve, provided by the manufacturer, in Fig. S2*A*. This curve is a function that maps the hub-height wind speed V to turbine power at that time, i.e. $P = f(V)$. Manufacturers typically provide a graphic of the function that maps wind velocity to power output. Here we digitized the Repower 5 M power curve for interpolation of wind speeds. An alternative is to derive a multiparameter curve to compute $P = f(V)$ (8).

Looking back at Fig. S1 briefly, note the horizontal dashed lines at 3.5 m s^{-1}, representing the turbine cut-in speed and at 13 m s^{-1}, the rated power. The figure shows that, most of the time at the sampled sites, the wind speed falls between these design parameters.

Patterns of Power Generation. In this section we first analyze the seasonal patterns of wind energy and the correlation of the power generated by different stations distributed along the coast. Next we explore the effects that an offshore transmission grid has upon aggregate power produced by the entire array.

Seasonal variability of wind and power generation. Summary averages over the entire 5-yr study period are shown in Table S2, specifically, the average wind speed, the average power output per 5 MW turbine and the "capacity factor." The capacity factor is a standard measure for wind power analysis. It is a dimensionless quantity, defined as average output (in MW$_a$) over maximum output (in MW); thus, if a 5 MW turbine produces an average of 2 MW$_a$ throughout a year, its capacity factor in that location is 0.40. (The actual calculation method is to take a year's total energy produced in MWh, and divide that quantity by the rated power in MW times 8,760 h/yr.)

Comparing annual measures in Table S2, we see that station S6 off Cape Hatteras has the highest wind speeds $V = 8.9$ m s^{-1}, the highest average power output $P = 2.3$ MW, and the highest capacity factor CF $= 0.46$.

In annual averages, the more northerly stations, from North Carolina (S5) through Maine (S11) have higher wind speeds than the southern ones. This is particularly evident during the winter; stations off Maine (S11) reach wind speeds of 11 $m\,s^{-1}$, a mean power production of 3 MW and a CF of 0.6, while winds off Georgia (S4) are $V = 7\ m\,s^{-1}$, $P = 1.5$ MW with CF $= 0.3$.

In summer, the central stations (S4–S6) produce the most power; in autumn, average production is most similar among stations. Because of these seasonal differences, interconnection of power generation would have some seasonal leveling as well as the shorter-term leveling we focus upon in the main article.

The main text provided several graphical means for comparing the power output of individual stations with the power output of the entire grid. Fig. S3 gives an additional graphic, a generation duration curve. This is an inverse cumulative probability distribution of turbine power, as used in some recent wind resource studies (8). Each point on the abscissa represents the percentage of time in a year that the power from a turbine (or connected group of turbines) is greater or equal to the corresponding ordinate capacity factor. That is, Fig. S3 plots the fraction of time that the turbine, or aggregate, produces that much or more. Thin lighter color lines are individual turbine sites, while the thick black line is the aggregate capacity factor of the entire Atlantic Transmission Grid.

For illustration, we first use the duration curve in Fig. S3 to examine individual locations. Suppose, for example, that a CF of 0.2 is sought. By looking from the 0.2 on the *y* axis, and moving to the right, the first line encountered, the worst performing individual turbine (dark blue line), achieves CF of at least 0.2 during 45% of the time. The best individual turbine, the light green line, achieves CF ≥ 0.2 about 63% of the time. By contrast, the Grid (black line) produces CF ≥ 0.2 for 80% of the time, considerably better than the best individual station comprising it. For the high CF values, the reverse is true—every one of the individual turbines produces full power more frequently than does the grid together.

Some of our figures in the article use stations S2 and S10 as diverse illustrative examples. Table S2 shows that S2 is the second lowest in CF and average power output, whereas S10 is the second highest. They coincidentally are also one off from the ends of the extent, thus experiencing different weather. Thus they are good for illustration of diverse and low-correlation sites. For summary and quantitative measures, we use all stations.

Graphic overview of all 5 yr data. As noted in the article, we tabulated missing periods of data, and hours of power below 5% of capacity, for the entire 5 yr. We also analyzed whether the missing periods were unrepresentatively concentrated in a single season. The graphical representation of this analysis is shown in Fig. S4, with tabulations noted on the right margin.

1. NDBC Web site: http://www.ndbc.noaa.gov.
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4. Barthelmie RJ, Courtney MS, Højstrup J, Larsen SE (1996) Meteorological aspects of offshore wind energy: Observations from the Vindeby wind farm. *J Wind Eng Ind Aerod* 62:191–211.
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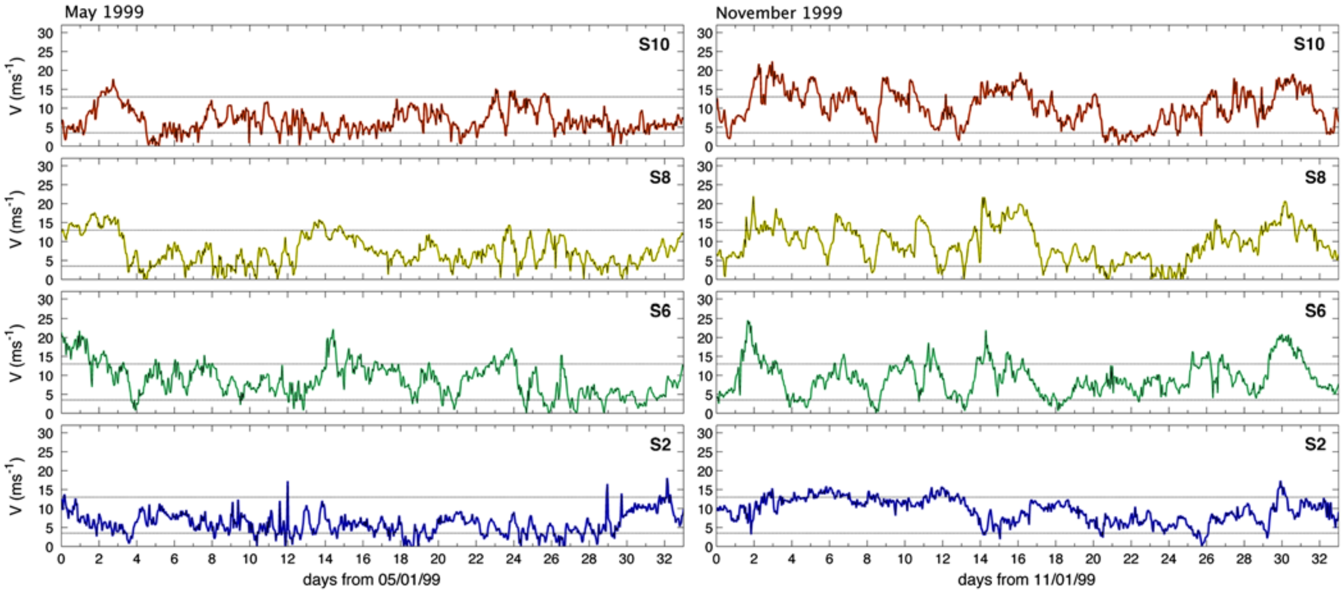

Fig. S1. Wind speed at hub-height for four stations along the eastern continental shelf of the United States. Left and right panels show nearly a month of data respectively for May and November of 1999. Station positions are shown on Fig. 1 and Table S1.

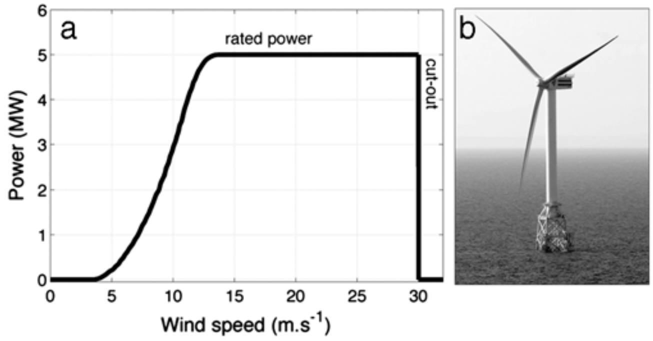

Fig. S2. (*A*) The REpower 5 M turbine power-curve. (*B*) Photo of a REpower 5 M offshore turbine from the Beatrice project installed 25 kilometers off the Scottish East Coast and at a water depth of 45 m (Photo Copyright REpower AG Systems, used with permission).

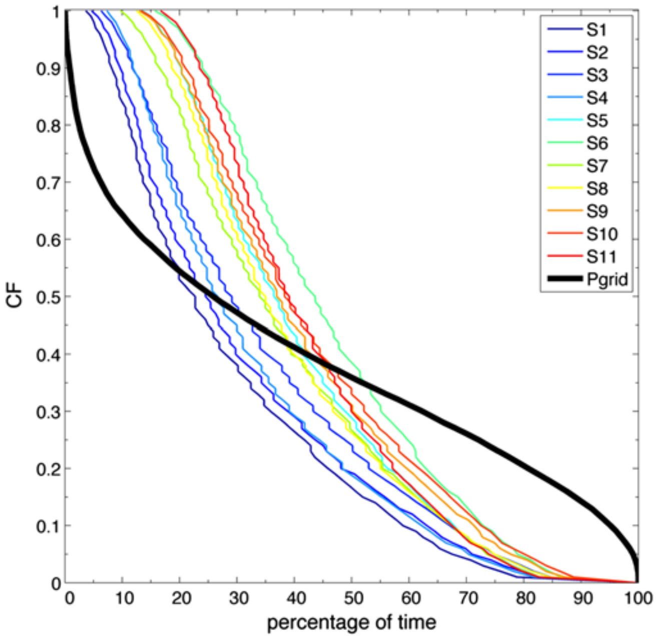

Fig. S3. Generation duration curves for each of the 11 stations (thin colored lines—colors match stations in Fig 1) and for P_{grid} (thick black line)

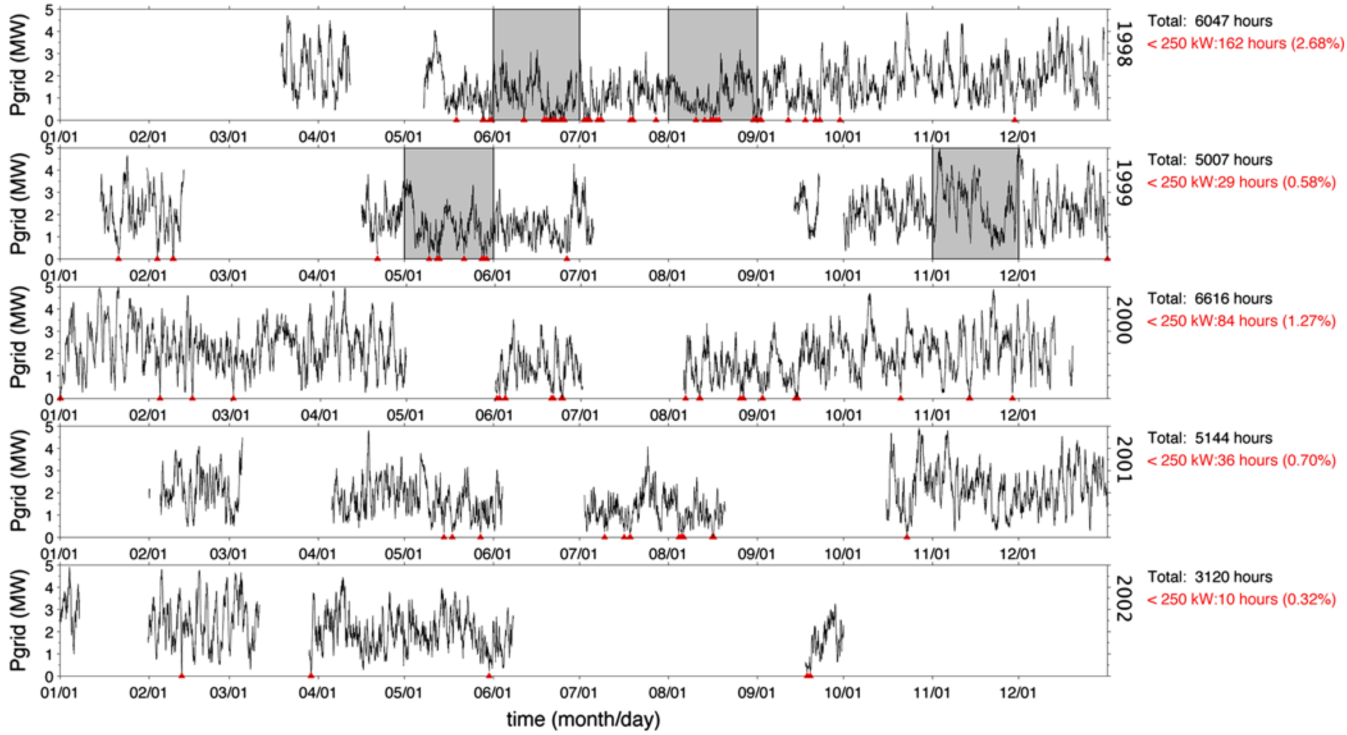

Fig. S4. Transmission grid average power generation for 1998 to 2002. Times for which data from one or more stations was missing are indicated by gaps in the plotted line. The red triangles indicate the periods when the power was below 250 kW (<CF 5%). The numbers of hours of observations (nonmissing data) and hours of low generation are indicated on the right of each panel.

Table S1. Selected offshore meteorological stations

Station	NDBC	Longitude	Latitude	z_{ref} (m)	Depth (m)	Type
S1	smkf1	−81.110	24.627	48.5	7.0*	tower
S2	fwyf1	−80.097	25.590	43.9	10.0*	tower
S3	41009	−80.175	28.509	5.0	41.5	buoy
S4	41008	−80.871	31.402	5.0	18.0	buoy
S5	fpsn7	−77.590	33.485	44.2	20.0*	tower
S6	dsln7	−75.297	35.153	46.6	19.0*	tower
S7	chlv2	−75.710	36.910	43.3	19.0*	tower
S8	44009	−74.702	38.464	5.0	28.0	buoy
S9	alsn6	−73.800	40.450	29.0	29.0*	tower
S10	buzm3	−71.033	41.397	24.8	3.0*	tower
S11	44005	−69.140	43.189	5.0	201.2	buoy

Shown are name, NDBC code, geographical coordinates, anemometer height z_{ref} (m), water depth (m) and type of station (buoy or tower). Station depths marked with an (*) are derived from the General Bathymetric Chart of the Oceans (GEBCO) bathymetric dataset, available at http://www.gebco.net.

Table S2. Seasonal and yearly mean wind speed ($m\,s^{-1}$), mean turbine production (MW), and turbine Capacity Factor (CF)

Season	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	Mean	N
Wind speed ($m\,s^{-1}$)													
Spring	6.81	7.45	7.79	7.14	8.72	9.5	8.59	7.85	8.51	8.59	7.94	8.08	6918
Summer	5.12	5.61	6.03	7.34	7.23	7.73	6.98	6.78	7.38	7.06	6.13	6.67	5709
Autumn	7.77	7.93	8.43	7.85	7.93	8.25	7.45	8.5	8.46	8.95	8.89	8.22	7350
Winter	7.62	7.68	8.04	7.12	9.29	10.16	8.72	9.33	9.38	9.83	11.03	8.93	5957
Yearly	6.9	7.23	7.64	7.38	8.3	8.91	7.94	8.14	8.44	8.64	8.52	8.00	25934
Turbine power (MW)													
Spring	1.42	1.63	1.78	1.48	2.18	2.56	2.22	1.82	2.09	2.12	1.89	1.93	6918
Summer	0.64	0.77	0.95	1.51	1.52	1.81	1.43	1.34	1.57	1.41	1.10	1.28	5709
Autumn	1.74	1.80	2.06	1.79	1.83	1.97	1.65	2.11	2.09	2.31	2.31	1.97	7350
Winter	1.68	1.72	1.90	1.54	2.45	2.81	2.24	2.46	2.46	2.63	3.09	2.27	5957
Yearly	1.40	1.51	1.70	1.59	2.00	2.29	1.89	1.94	2.06	2.13	2.11	1.87	25934
Capacity Factor (CF)													
Spring	0.28	0.33	0.36	0.30	0.44	0.51	0.44	0.36	0.42	0.42	0.38	0.39	6918
Summer	0.13	0.15	0.19	0.30	0.30	0.36	0.29	0.27	0.31	0.28	0.22	0.25	5709
Autumn	0.35	0.36	0.41	0.36	0.37	0.39	0.33	0.42	0.42	0.46	0.46	0.39	7350
Winter	0.34	0.34	0.38	0.31	0.49	0.56	0.45	0.49	0.49	0.53	0.62	0.45	5957
Yearly	0.28	0.30	0.34	0.32	0.40	0.46	0.38	0.39	0.41	0.43	0.42	0.38	25934

N refers to the number of hourly observations.