The effect of long-distance interconnection on wind power variability

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Abstract

We use time- and frequency-domain techniques to quantify the extent to which long-distance interconnection of wind plants in the United States would reduce the variability of wind power output. Previous work has shown that interconnection of just a few wind plants across moderate distances could greatly reduce the ratio of fast- to slow-ramping generators in the balancing portfolio. We find that interconnection of aggregate regional wind plants would not reduce this ratio further but would reduce variability at all frequencies examined (connecting ERCOT and CAISO, for example, would reduce variability by 32 % in CAISO and 17 % in ERCOT). Interconnection of just a few wind plants reduces the average hourly change in power output, but interconnection across regions provides little further reduction. Interconnection also reduces the magnitude of low-probability step changes and doubles firm power output (capacity available at least 92 % of the time) compared with a single region. First-order analysis indicates that balancing wind and providing firm power with local natural gas turbines would be more cost-effective than with transmission interconnection. For net load, increased wind capacity would require more balancing resources but in the same proportions by frequency as currently. This justifies treating wind as negative load.

Keywords: wind power variability, net load variability, Electric Reliability Council of Texas, California ISO, Midwest ISO, Bonneville Power Authority

1 Introduction

Wind power is among the least costly and most developed renewable energy technologies, which renders it well suited to fulfilling the renewable energy targets currently implemented in most U.S. states. Between 2005 and 2010, installed wind capacity in the U.S. increased by a factor of 4.4 and net wind generation by a factor of 5.3 (Wiser & Bolinger 2011). As wind capacity continues to grow, the variability and intermittency of wind power can create challenges for grid operators. High frequency, second-to-second fluctuations can increase the need for frequency regulation, and lower frequency (hourly to seasonal) fluctuations can change the capacity factors of baseload generators and in severe cases affect reliability. Wind integration studies have suggested that building transmission capacity to interconnect wind power plants could greatly smooth wind power output (Zavadil 2006, IEA 2005, EnerNex 2011, Energy 2010, EERE 2008), but few explicitly account for the frequency at which the variability occurs.

Katzenstein et al. (2010) performed the first frequency-dependent analysis of the smoothing effect of interconnecting wind plants. Using 15-minute energy output data from 20 wind plants in the Electric Reliability Council of Texas (ERCOT), Katzenstein et al. (2010) find that at a frequency of $(1\ \mathrm{h})^{-1}$ (2.8×10^{-4} Hz) interconnecting just four wind plants reduces the ratio of high- to low-frequency variability by 87 % compared with a single wind plant, but that connecting additional wind plants yields diminishing returns. At a frequency of $(12\ \mathrm{h})^{-1}$, interconnecting four wind plants reduces this ratio by only 30 % compared with a single plant. Variability reduction was found to depend on factors such as size and location of wind plants as well as the number interconnected.

This result highlights the importance of time scale in characterizing wind power smoothing and suggests that interconnecting a relatively small number of wind plants could achieve most of the reduction in the ratio of high- to low-frequency variability that would result from interconnecting many more. This ratio is one determinant of the relative requirements for fast and slow ramping sources required to compensate for wind's variability. Katzenstein et al. (2010) limited their study to west-central Texas, where there may be a correlation of weather and wind patterns, and did not examine the effect of wind plant interconnection on the variability of net load (electricity load minus wind power output). Building upon Katzenstein et al. (2010), our work uses frequency-domain analysis to examine both the smoothing effect of interconnecting wind plants across greater distances and the variability of net load under greater wind power penetration (see Supporting Information S2).

Sørensen et al. (2008) use frequency domain techniques to analyze the reduction in wind power output variability due to interconnecting individual wind turbines within a single offshore wind plant. The smoothing effect is modeled at time scales from minutes to hours and found to be strongest at high frequencies. The analysis and results of Sørensen et al. (2008) are similar to ours despite the difference in scale, highlighting the fractal property of wind energy.

Wind power variability studies utilizing exclusively the time domain include Giebel (2000), Ernst et al. (1999) and Sinden (2007). These studies find that correlation of wind power output decreases predictably as the distance between the wind plants increases but is still slightly positive even for widely separated plants.

Further characterizing geographic smoothing, Degeilh and Singh (2011) introduce a method for selecting from a set of geographically separated wind sites to minimize wind power output variance and show that achieving this objective yields the smallest loss of load probability (LOLP) as well. Kempton et al. (2010) use offshore meteorological buoy data from 2500 km. along the U.S. east coast to analyze the effect of interconnecting 11 wind sites and find that interconnection reduces the variance of simulated power output, slows the rate of change, and eliminates hours of zero production during the five-year study period. Kempton et al. (2010) conclude that the cost of mitigating wind variability with long-distance transmission interconnection has a cost on par with current methods of balancing wind. Dvorak et al. (2012) use mesoscale wind data to find the best locations for four offshore wind plants near the U.S. east coast to reduce variability, hourly ramp rates, and hours of zero power. The latter two studies approximate wind power output using wind speed measurements taken significantly below turbine hub height. Though buoy data are the best available until hub-height met masts become widespread and generate an extensive record, they are often of poor quality and can exaggerate estimated wind power variability (Holttinen 2005).

In this paper, we analyze the extent to which interconnecting wind plants over broad geographical regions of the United States will reduce variability of wind power output. We use simultaneous wind energy data from four regions (the Bonneville Power Authority (BPA), the Electric Reliability Council of Texas (ERCOT), the Midwest ISO (MISO), and the California ISO (CAISO)) and apply methods suggested in Katzenstein et al. (2010) and Sørensen et al. (2007). The analysis informs the question of whether increasing interregional transmission capacity is an effective means of smoothing wind power output. Section 2 describes the data used, Section 3 details the methods, and Sections 4 and 5 present results and discussion.

The observed data show that interconnection of regional wind resources increases the percentage of firm wind power capacity, reduces the coefficient of variation of wind power output, and reduces the likelihood of extreme step changes. Although step changes are one metric for evaluating variability, frequency-domain analysis can help establish the portfolio of generation needed to compensate for variability. If the amplitude of high frequency variations is the same as that of low frequency variations, as much fast-ramping generation must be available as slow-ramping generation. On the other hand, if interconnection is able to reduce the fast fluctuations, much less fast-ramping generation will be required. Katzenstein et al. (2010) found that interconnecting 4 or 5 wind plants achieves the majority of the reduction in the ratio of high to low frequency fluctuations. Because an asymptote is quickly reached, it is not surprising that we find large scale interconnection does not further reduce this ratio, and that variability reduction at the relevant frequencies could be achieved as effectively by interconnection within regions as between regions. Likewise, inter-regional interconnection does not significantly affect mean step changes in hourly wind power output; the majority of the reduction in mean step changes is achievable through interconnection of wind plants within single regions.

2 Data

We use wind energy output and load data from BPA, CAISO, ERCOT, and MISO (see Supporting Information S1.1). Throughout the analysis, 2009 is emphasized since it was the only year for which data from all four regions were available. When analyzing multiple regions simultaneously, higher-frequency data are summed to hourly, the highest common frequency, and data are adjusted by time zone to coincide. Single missing hourly data points were approximated as the mean of the preceding and following values, and longer gaps were excised. When feasible, analysis of a single region across years characterizes interyear variability.

Figure 1 shows a map of the four control regions with wind plant locations and Supporting Information S1.1 contains relevant wind and load statistics.

3 Methods

The power spectral density (PSD) gives a quantitative measure of the strength of wind power fluctuations across a range of frequencies. PSDs of wind power output often contain a peak at $(24\ \mathrm{h})^{-1}$, reflecting daily periodicity (see Supporting Information Figure S1). Wind power PSDs have a negative slope in log-log space: power fluctuations at frequencies corresponding to 10 minutes, for example, are at least a factor of a thousand smaller than those at periods of 12 hours. This property has important practical consequences: if the PSD of wind were flat (white noise), large amounts of very fast-ramping sources would be required to buffer the fluctuations of wind power. The negative slope of the PSD implies that slow-ramping resources such as coal or combined cycle gas plants can compensate for most of wind power's variability, with less reliance on fast-ramping resources such as

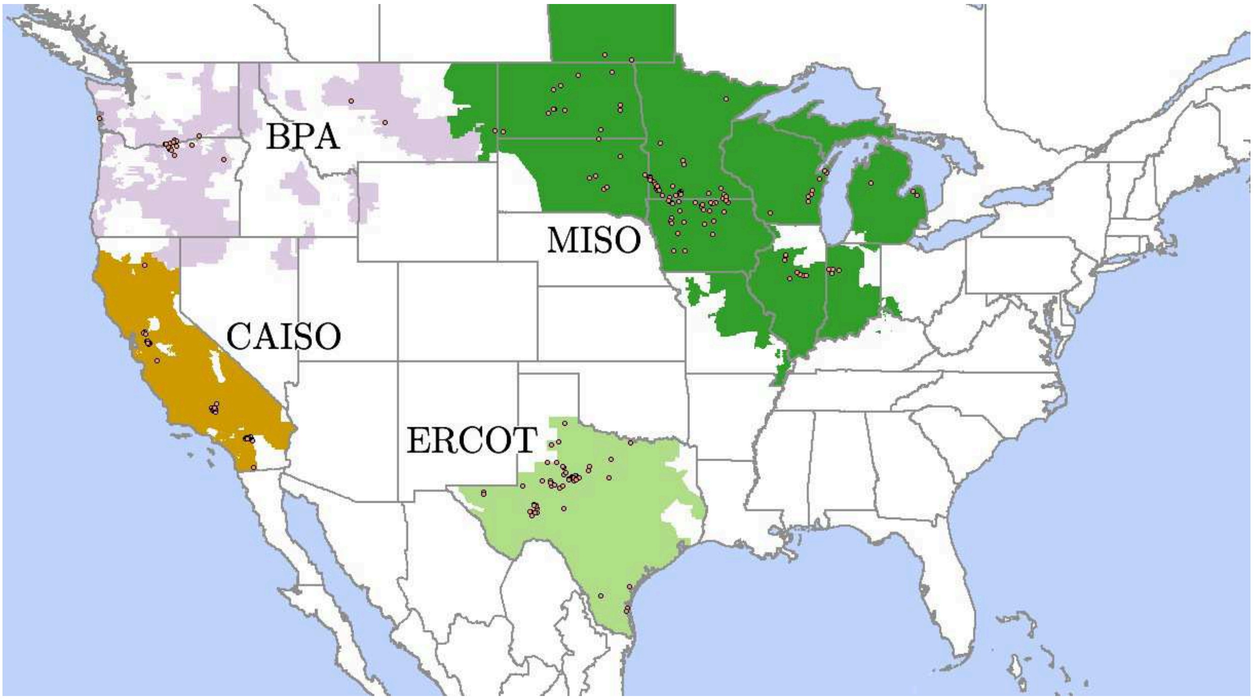

Figure 1: The area spanned by each region and the wind plants it contains.

batteries and peaker gas plants. The Kaimal spectrum, with a slope of $-5/3$ at frequencies above 24 h^{-1} in log-log space, has been shown to approximate the PSD of power output from a single wind plant (Katzenstein et al. 2010) (see Supporting Information S1.2).

The absolute values of the PSDs, especially at higher frequencies, cannot be directly translated into the wind-balancing resources required at those frequencies. Rare but steep rises or falls in wind power output can increase PSD values at high frequencies such that they no longer reflect general variability patterns. To gain insight into the ideal composition of a wind-balancing portfolio, we observe that the power spectrum for a single, linear ramping generator would be proportional to f^{-2} (Apt 2007). A generator such as a natural gas plant, sized so that its ramp rate matches wind's hourly variability, would therefore have nearly twice the capacity necessary to compensate for wind fluctuations observed at daily frequencies. Balancing wind with a portfolio containing fast-ramping resources such as batteries, fuel cells, and supercapacitors, in addition to slower-ramping resources, would avoid the unnecessary expense incurred by building a single type of linear ramp rate generator that would have excess capacity at low frequencies (Apt 2007).

We analyze PSDs of wind energy output of single regions as well as the summed output of two to four regions, representing interconnection by increased transmission capacity. The inertial subrange is the range of frequencies above the corner frequency, where the power spectrum transitions from zero to negative slope at roughly $(24\text{ h})^{-1}$ (see

Supporting Information S2). The PSD slope in the inertial subrange reflects the relative proportion of fast- and slow-ramping units required to balance wind power output. A slope steeper than $-5/3$ implies that high-frequency fluctuations are weaker relative to low-frequency fluctuations than expected for a single wind plant. This smoothing effect at high frequencies is due to the geographic diversity of wind plants. If the slope is steeper for summed data than for individual regions, then interconnection across regions would reduce the relative variability of wind power output at higher frequencies more than further interconnection within the same region. PSD slopes were found using least-squares linear regression.

4 Results

4.1 Coefficients of variation

Figure 2 shows the coefficients of variation (the standard deviation divided by the mean, abbreviated CV) of 2009 wind power output of each region and their aggregate. Since regions with larger mean wind power output tend to have more wind plants with greater geographic dispersion, the CV generally decreases as mean wind power output increases. The reduction in CV due to pairwise interconnection ranged from 3 % for CAISO (through interconnection with BPA) to 48 % for BPA (through interconnection with MISO; see Figure 2). Most reductions were similar to those expected for uncorrelated wind power output, with the exception of BPA and CAISO, whose CV was 16 % higher than that expected for zero correlation The correlation coefficient for these two regions was $\rho = 0.32$, likely due to similar east-west moving fronts and sea breeze effects (see Supporting Information S1.5). While interconnection of these two regions would substantially reduce wind variability in BPA, it would leave CAISO wind variability nearly unchanged.

Interconnection of all four regions would reduce the coefficient of variation by the greatest amount in BPA (58 %) and the least in ERCOT (28 %). The observed correlation of the four interconnected regions is positive and the coefficient of variation is 19 % above that expected for uncorrelated wind power output. Supporting Information S1.5 contains further analysis of the correlation of wind power output between regions.

4.2 Frequency domain analysis

Figure 3(a) shows the PSDs of 2009 wind power output for all four regions and their aggregate as well as a reference Kaimal spectrum (the expected PSD for a single wind plant, here normalized to the summed data). At frequencies higher than $(24\text{ h})^{-1}$, the aggregated regions show less variability relative to lower frequencies than the reference

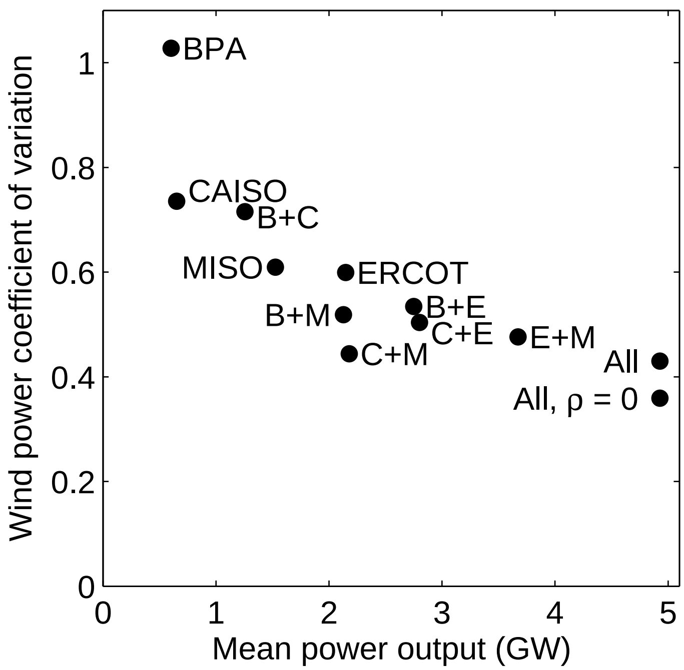

Figure 2: Coefficient of variation (standard deviation divided by mean) of 2009 wind power output for each of the four regions, pairs of regions, and the four regions combined. Pairs of regions are denoted by the first letters of their acronyms separated by the symbol +. "All, $\rho = 0$" refers to the expected coefficient of variation for the aggregated regions if the individual regions were pairwise uncorrelated. Positive correlations between regional wind power outputs raise the coefficients of variation of summed wind power above that expected for uncorrelated power output. By this measure BPA had the most volatile wind power output, with its standard deviation approximately equal to its mean.

Kaimal spectrum, as do the individual regions (whose reference Kaimal spectra are not shown). This smoothing pattern is the result of interconnection of individual wind plants within each region, whose power output shows less correlation at high frequencies than at low frequencies.

The similarity of the PSD curves in log-space in Figure 3(a) suggests that the variability reduction due to interconnection shown in Figure 2 takes place uniformly across all frequencies examined and that interconnection of regions, unlike interconnection of just a few wind plants, does not reduce the ratio of high- to low-frequency variability for the range of frequencies examined. This effect can be quantified by the slopes of log PSDs in the range of $(24\text{ h})^{-1}$ to $(2\text{ h})^{-1}$ (corresponding to the inertial subrange), which reflect the relative variability of power output at the frequencies within that range. Slopes of less than $-5/3$ (the value for a single wind plant) indicate smoothing at higher frequencies due to geographical diversity of interconnected wind plants. The slopes of the log PSDs for individual and interconnected regions are shown in Figure 3(b).

F-tests were used to evaluate the null hypothesis that the PSD slopes in the inertial subrange were the same for individual regions as for combinations of regions. For each group of regions except BPA and CAISO, the null hypothesis failed to be rejected at the 5 % significance level for at least one of the regions tested against the aggregate. The slope in the inertial subrange for BPA combined with CAISO (-2.61) was significantly different from those of both BPA (-2.51) and CAISO (-2.71). In all cases, although interconnection would reduce variability at all frequencies examined, it would not reduce the slope in the inertial subrange compared with each of its constituent regions. This result indicates that interconnection across regions would not change the proportions of fast- and slow-ramping resources necessary to balance wind power output, and that interconnecting more wind plants within the same region could similarly reduce variability and incur much lower transmission cost.

Figure 3(b) shows that the log slopes of PSD estimates in the inertial subrange can vary between years, implying that the mix of generators, storage, and demand response necessary to compensate for variability of a given amount of wind power can differ from year to year. For the years with data available, these differences are significant at the 5 % level for BPA and CAISO but not for MISO. For ERCOT, differences between years tend to be significant, with the exception of 2007/2010 and 2008/2009.

The PSD slope for BPA wind power output was greater than or equal to that of the other regions for each year examined, indicating comparatively less smoothing due to interconnection of wind plants within BPA. The proximity of the BPA wind plants could expose them to similar weather patterns, limiting the degree of smoothing as a result of interconnection. This effect could also help explain the higher coefficient of variation for

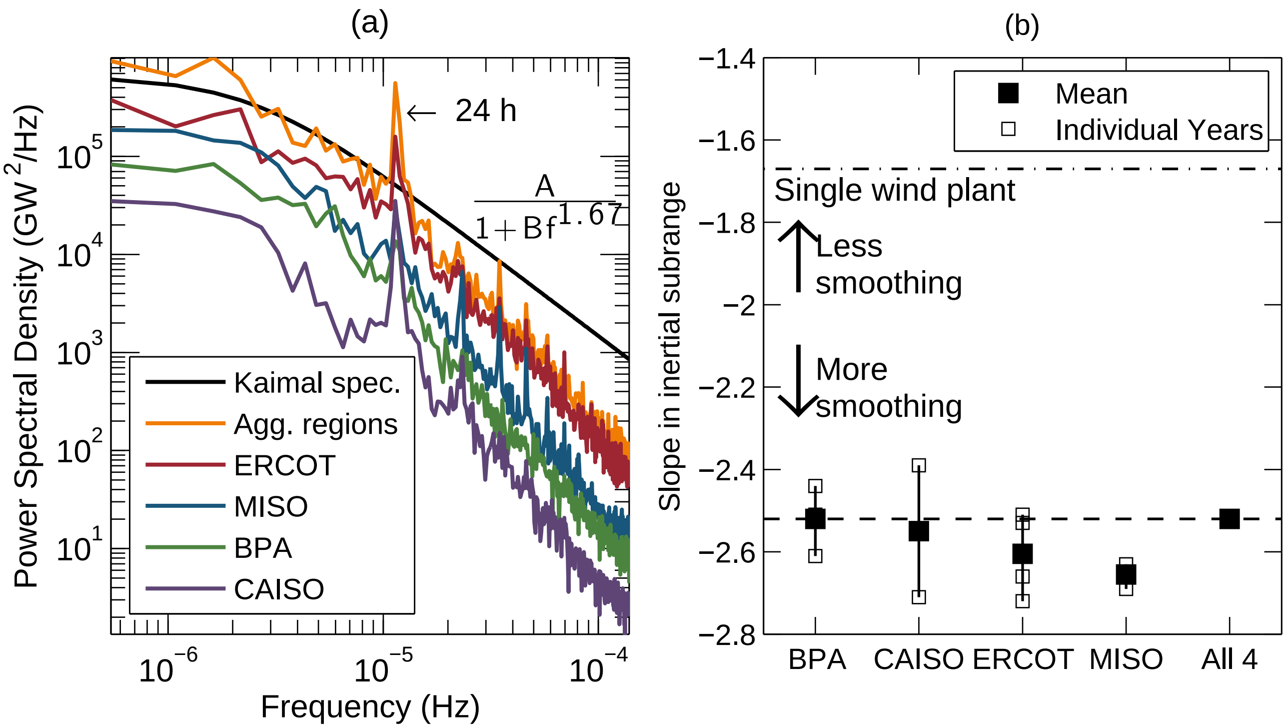

Figure 3: (a) PSDs for 2009 wind power output of each region and the aggregate of all four regions plotted on log-log axes. The displayed Kaimal spectrum equation approximates the PSD for a single wind plant (fitted parameters are $A = 5.84\times10^5$ and $B = 2.06\times10^9$). In the inertial subrange (frequencies higher than $(24\text{ h})^{-1}$), the summed power output shows less variability than that of a single wind plant. The legend lists data as they appear from top to bottom. (b) Slopes in the inertial subrange for each region and the interconnected regions for all years of available data and the means over time. The slope for the interconnected regions in 2009 is within the range of slopes for individual regions in other years for which data were available.

BPA than for the other regions.

To summarize, our results suggest that interconnecting multiple wind plants across the four U.S. regions examined would reduce the coefficient of variation of wind power output, smoothing wind power output at all frequencies examined. Interconnection would not, however, reduce the ratio of high frequency to low frequency variability in wind power output beyond the reduction found by Katzenstein et al. (2010) for ERCOT wind plants.

4.3 Wind power duration curve

Figure 4 shows a duration curve for 2009 wind power output. Adopting the definition of "firm power" from Katzenstein et al. (2010) as capacity available 79 to 92 % of the time, we find that the interconnected regions have the greatest amount of firm power, with 17 % of installed wind capacity available 79 % of the time and 12 % of capacity available 92 % of the time. MISO, the region with the firmest wind power output as well as the the least likelihood of extreme hourly step changes and lowest slope in the inertial subrange, had 13 % of capacity available 79 % of the time and 6 % of capacity available 92 % of the time. BPA had the least amount of firm wind power, with only 2 % and 0.2 % of capacity available at the ends of the firm power range, consistent with the finding of Katzenstein et al. (2010) for 2008 data (3 % and 0.5 %). For 2008 ERCOT data, Katzenstein et al. (2010) found 10 % and 3 % of installed capacity available at the limits of the firm power range; for 2009 data, we find 10 % and 4 %. While interconnection of all four regions would at least double the fraction of capacity available 92 % of the time in each region, the gain in firm power (which amounts to approximately 1.5 GW above the sum of that of the individual regions) is unlikely to be sufficient to cover the cost of necessary transmission capacity.

4.4 Step change analysis and balancing cost comparison

Step changes of wind power output were calculated as the difference between power output in consecutive hours as a fraction of installed capacity. Interconnection of all four regions was found to produce negligible additional reduction in mean step changes compared with that achieved in a single region. BPA and ERCOT have the highest likelihood of large hourly step changes and MISO and the aggregated regions the lowest (see Supporting Information S1.4).

We wish to evaluate the cost-effectiveness of smoothing wind power output with increased transmission capacity between the regions with the greatest wind variability, BPA and ERCOT. We calculate the length of high-voltage transmission with cost equivalent to that of a peaking gas turbine sized to mitigate negative 99^{th} percentile step changes in BPA and ERCOT, plus a combined-cycle gas turbine providing firm capacity equivalent to

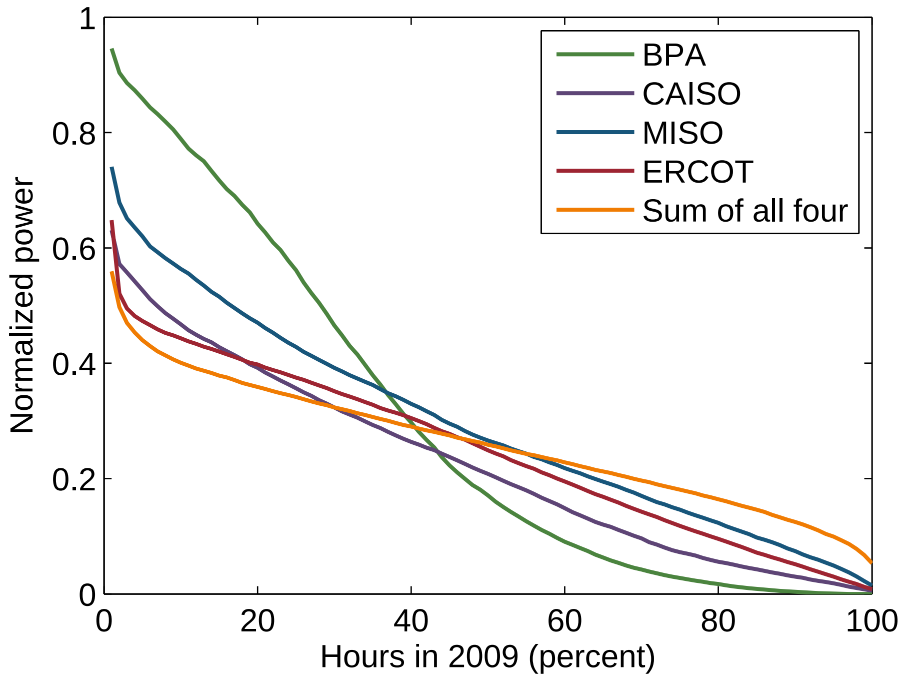

Figure 4: Duration curve for 2009 wind power output. The interconnected regions show the greatest percentage of firm power (capacity available 79 to 92 % of the time) and BPA the least.

what the interconnected regional wind power output could provide. We find that the cost of the gas turbines would only cover 490 to 740 miles of transmission capacity (630 to 960 miles if emissions damages are included), whereas BPA and ERCOT are separated by 1400 miles (see Supporting Information S1.6 for details of the cost calculation). This first-order analysis suggests that local gas is a more cost-effective method of balancing low-probability step changes and providing firm power than increased transmission capacity.

5 Discussion and Conclusion

Frequency domain analysis shows that fluctuations in wind power are not white noise. Fluctuations in aggregate regional wind power output are between three and five orders of magnitude stronger at daily frequencies than at hourly frequencies (see Figure 3). The relative strength of low-frequency fluctuations of wind power output yields the important result that wind power can be balanced to a large extent by slow-ramping generators such as coal plants and combined-cycle natural gas plants.

Interconnection of wind plants within a single region would further reduce the ratio of fast- to slow-ramping generators necessary to balance wind power output, since across short distances wind's high-frequency fluctuations cancel each other more effectively than its low-frequency fluctuations. Our work demonstrates that interconnection of aggregate regional wind power output would provide no further reduction in the ratio of high- to low-frequency fluctuations, and therefore the ratio of fast- to slow-ramping generators in the balancing portfolio, than the reduction obtained from interconnecting wind plants within a region.

Nevertheless, benefits of interconnecting aggregate regional wind plants include variability reduction at all frequencies examined (as measured by the coefficient of variation), reduction in the likelihood of extreme step changes in wind power output, and doubling of the fraction of wind capacity available 92 % of the time compared with the maximum of the single regions.

BPA is the region that would benefit most from interconnection with other regions. However, BPA is also the only region with substantial hydropower capacity, including pumped storage. Hydropower is a low-emissions technology that ramps quickly enough to follow fluctuations in wind power output, and may be a more successful and cost-effective method for integrating BPA wind power than long-distance interconnection.

Net load (load minus wind generation) shows the same relative proportions of high and low frequency fluctuations regardless of wind capacity, such that the proportion of balancing resources required to compensate for wind variability will be roughly constant as wind capacity grows (see Supporting Information S2). This finding supports the treatment of wind power as negative load.

A first-order analysis shows that for BPA and ERCOT, the cost of mitigating wind's low-probability step changes and providing equivalent firm power is considerably lower with natural gas turbines than with interconnection of aggregate regional wind plants.

The availability of higher resolution data over a longer time span would refine these conclusions, although the consistency of the findings and their similarity across 2008 and 2009 argue for the robustness of the principal conclusions.

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Table S1: Summary statistics for wind power in the four regions examined in 2009.

	BPA	CAISO	ERCOT	MISO
Installed wind capacity (MW)[a]	2,100	2,200	8,400	6,600
Maximum hourly wind (MWh)	2,300[b]	1,900	6,000	5,400
Capacity factor	0.29	0.22	0.24	0.29
Average load (MW)	6,200	26,600	35,100	62,600
Average wind/load	0.10	0.025	0.067	0.028

[a] 2009 yearly average installed wind capacity.

[b] In BPA, installed wind capacity increased sufficiently during 2009 such that the maximum power output, which occurred near the end of the year, exceeds the average installed capacity.

Supporting Information

S1 Wind power variability

S1.1 Data

Table S1 gives regional wind and load statistics for 2009 and Table S2 summarizes the time spans, sampling frequencies, dropouts, and origins of the data
(BPA 2011, CAISO 2011, ERCOT 2011, MISO 2011).

S1.2 PSD and Kaimal spectrum approximation

We use the periodogram approximation to the power spectral density:

$$P(f) = \frac{1}{NF_s}\left|\sum_{n=0}^{N-1} x_n e^{-j2\pi fn/F_s}\right|^2 \tag{1}$$

in which f is frequency in Hz, N is the number of samples, F_s is the sampling frequency in Hz, and x_n is the time series.

To analyze smoothing of wind power output in the frequency domain, we first estimate a PSD of a single wind plant to serve as a standard for comparison. Apt (2007) showed that fluctuations in wind power output are not white noise, which has equal power at all frequencies; rather, they are much stronger at low frequencies (signals with PSDs of that character are termed red noise). As discussed in the text, this has the important implication that the majority of wind's variability can be balanced by slow-ramping

Table S2: Summary of data sampling frequencies, gaps, and origins. Wind and load data dropouts occurred simultaneously for all but CAISO 2010. No 2008 MISO load data or 2007-8 CAISO wind data were obtained. Gaps refer to the number of data points missing.

Region	Year(s)	Sampling frequency (min)	Sample gaps (longest consecutive)
BPA	2008	5	27 (12)
BPA	2009	5	48 (12)
BPA	2010	5	-
CAISO	2007	60	4 (1)
CAISO	2008	60	288 (6)
CAISO	2009	60	-
CAISO	2010	1	925 (789) wind; 553 (18) load
ERCOT	2007 - 2010	15	-
MISO	2008-2009	60	-

sources. As an example, we have examined a sample of 59 coal plants, and determined their ramp rates. The slowest-ramping one in our sample is a 600 MW coal plant with a ramp rate of 0.2 % per minute. That is, it can cycle 50 % of its power with a characteristic frequency of $\sim 7 \times 10^{-5}$ Hz. Referring to the PSD of wind power output (Figure S1 below or Figure 3(a) in the main text), we see that ramping a coal plant at that or lower frequencies can compensate for the great majority of wind's fluctuations.

The PSD of output from a single wind turbine follows the Kolmogorov spectrum, with slope $-5/3$ on a log-log plot, at frequencies corresponding to 30 s to 2.6 d. After Kaimal (1972) and later Katzenstein et al. (2010), parameters A and B in (2) are fit to the PSD of output from a single wind plant, such that at low frequencies the slope approaches zero and at high frequencies the slope approaches $-5/3$. The power spectrum described by (2) is termed the Kaimal spectrum, in which S is the power spectral density:

$$S(f) \approx \frac{A}{1 + Bf^{\frac{5}{3}}} \tag{2}$$

The parameter B determines the corner frequency, at which the PSD slope transitions from 0 to $-5/3$. The parameter A scales the amplitude. To obtain a standard for comparison for the remainder of the analysis, we fix B as the value for the wind plant in Snyder, Texas, which was the ERCOT wind plant found to best conform to the Kaimal spectrum. We scale A such that the integral of the PSD is the same as that of the Kaimal spectrum, giving the time-domain signals the same variance. Figure S1 shows the PSD and Kaimal fit for Snyder. To reduce noise, the year of data was divided into 16 segments, the

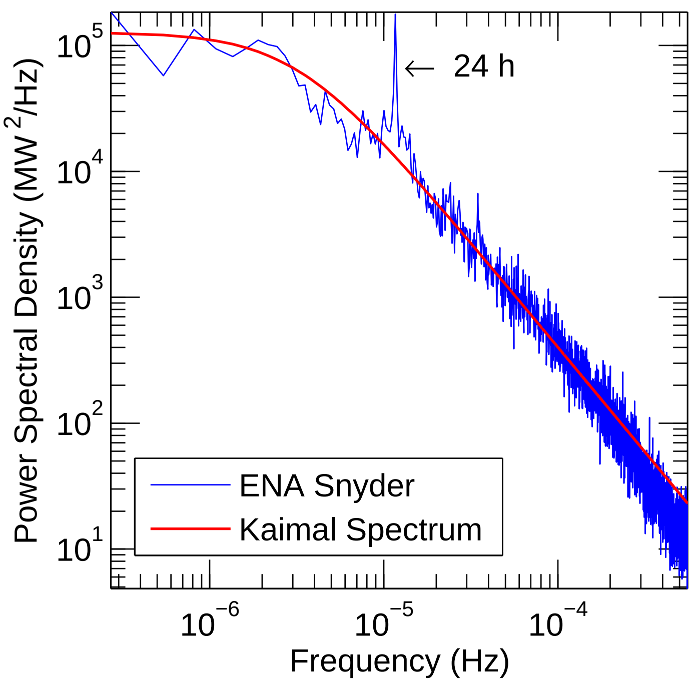

Figure S1: Kaimal approximation to the PSD of 15-minute wind energy data from a single 63 MW wind plant in Snyder, Texas (ERCOT). The peak at the frequency corresponding to 24 hours is highlighted, showing the strong daily periodicity in the wind power output. The fitted parameters are $A = 1.27 \times 10^5$ and $B = 1.47 \times 10^9$. The PSD was calculated with 16 segment averaging to reduce noise.

PSD calculated for each segment, and the final PSD obtained by taking the average over the segments.

The two distinct regions of slope, at frequencies above and below the corner frequency of about $(24\ \mathrm{h})^{-1}$, result from atmospheric properties at different spatial scales. Boer and Shepherd (1983) show that the energy spectrum of wind has a slope of $-5/3$ at high wavenumbers (spatial frequencies), for which its flows exhibit isotropic turbulence and transient behavior. This region, which corresponds to high-frequency fluctuations in wind speed, is not sensitive to season. At low wavenumbers (corresponding to low frequencies) where the PSD is flat, the energy spectrum varies seasonally and is largely determined by topography and thermal effects. Over the range of frequencies examined in this paper, wind power output inherits these properties.

S1.3 PSD slopes in the inertial subrange

Table S3 shows slopes of the log PSDs in the inertial subrange for wind power output of individual and interconnected regions. Slopes of less than $-5/3$ (the value for a single wind

Table S3: Log PSD slopes for frequencies from (24 h)$^{-1}$ to (2 h)$^{-1}$, in which a single wind plant follows the Kolmogorov spectrum (slope = -1.67).

Region	2007	2008	2009	2010
BPA	-	-2.44	-2.51	-2.61
CAISO	-	-	-2.71	-2.39
ERCOT	-2.72	-2.53	-2.51	-2.66
MISO	-	-2.63	-2.69	-
BPA and CAISO	-	-	-2.61	-2.43
BPA and ERCOT	-	-2.48	-2.52	-2.63
BPA and MISO	-	-2.46	-2.64	-
CAISO and ERCOT	-	-	-2.54	-2.40
CAISO and MISO	-	-	-2.70	-
ERCOT and MISO	-	-2.51	-2.50	-
BPA, CAISO, and ERCOT	-	-	-2.55	-2.44
BPA, CAISO, and MISO	-	-	-2.66	-
BPA, ERCOT, and MISO	-	-2.49	-2.50	-
CAISO, ERCOT, and MISO	-	-	-2.51	-
BPA, CAISO, ERCOT, and MISO	-	-	-2.52	-

plant) indicate reduction in the ratio of high- to low-frequency variability due to geographical diversity of interconnected wind plants. Although each individual region has a substantially lower PSD slope in the inertial subrange compared with a single wind plant, in pairwise linear hypothesis tests (F-tests), no set of interconnected regions has a significantly lower PSD slope than each of its constituent regions. This result implies that interconnection of two or more regions would not reduce proportions of fast- and slow-ramping resources necessary to balance wind power output.

S1.4 Step change analysis

S1.4.1 Methods

Step changes are calculated as the fractional changes in wind power output or load over a time interval:

$$\Delta P = \frac{P(t + \Delta t) - P(t)}{P_c} \tag{3}$$

$P(t)$ is the average power output over the time interval centered at t with length Δt. P_c is the installed wind power capacity.

The step change in wind power must be matched by an opposite change in load or interchange or by activation of balancing and regulation resources. We examine hourly step changes ($\Delta t = 1$ h) since that time scale is important to scheduling and ancillary service markets. While step changes by themselves are a crude measure of the strain wind power imposes on a system, operations personnel at RTOs have indicated that step changes are useful indicators of variability and they enable comparison with other wind variability studies (Wan 2004, Sørensen et al. 2007). While step changes as a fraction of load would also yield insight into the system response required to balance wind, step changes as fractions of installed capacity are akin to average ramp rates and thus facilitate comparison with other generators.

S1.4.2 Results

Mean hourly step changes were 3.0 to 4.3 % of installed capacity (positive) and 2.8 to 4.0 % of installed capacity (negative) for the individual regions. For the four interconnected regions, mean hourly step changes were 2.8 % (negative) and 3.0 % (positive) of installed capacity, indicating negligible benefit from interconnection. Wan (2004) found that individual wind plants in Iowa, Minnesota, and Texas had mean hourly step changes of 4.1 % to 6.1 % of maximum capacity, and that connecting four wind plants in Texas reduced mean step change to 3.7 %. The combined results imply that interconnecting more than four wind plants would produce diminishing marginal reductions of mean step changes. Mean negative step changes as a fraction of nameplate capacity were consistently less than mean positive step changes, suggesting that wind-balancing resources on average will be required to ramp down more quickly than they ramp up.

Figure S2 shows a duration curve for 2009 hourly step changes (as fractions of installed capacity) for each region and their aggregate (after Sørensen et al. (2007)). For clarity, the plot is cropped to show only positive step changes, though the portion of the plot showing negative step changes is roughly symmetrical. BPA and ERCOT have the highest likelihood of large hourly step changes, and MISO and the aggregated regions tend to have the lowest probability of extreme hourly step changes. Nevertheless, ERCOT's coefficient of variation is the lowest of the four regions (see Figure 2); although wind power output in ERCOT shows low variability in general compared with the other regions, its worst-case fluctuations tend to be more extreme. Supporting Information S2.2 contains a step change analysis of net load.

S1.5 Correlation of wind power output

Correlation coefficients for two wind power output time series X and Y were calculated as $\rho_{X,Y} = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i-\bar{X}}{s_X}\right)\left(\frac{Y_i-\bar{Y}}{s_Y}\right)$ in which n is the number of hourly data points, $\bar{X}$ and $\bar{Y}$ are the sample means of X and Y, and s_X and s_Y are the sample standard deviations of X

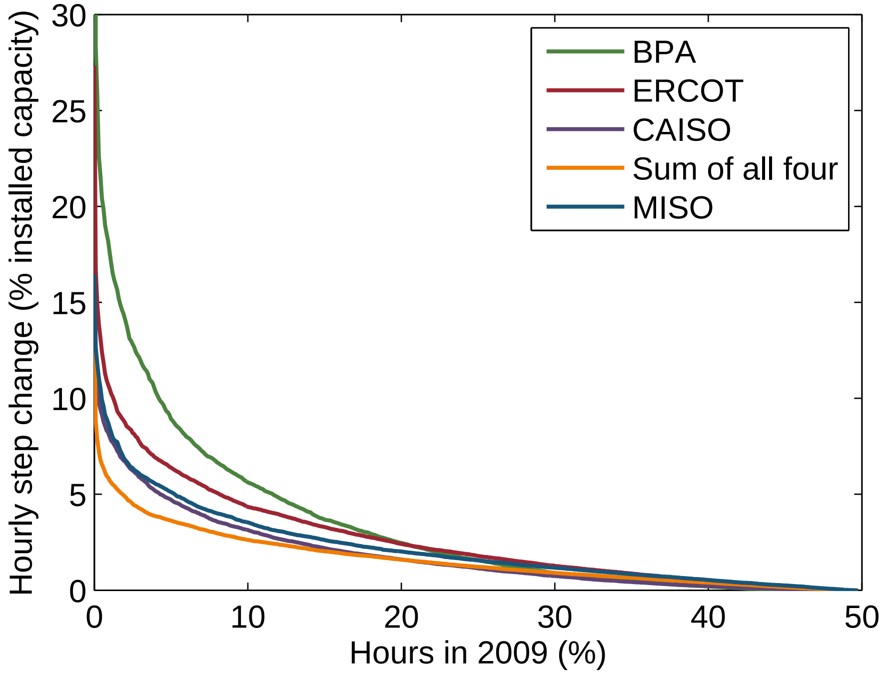

Figure S2: Duration curve for hourly step changes. BPA and ERCOT are the most likely to have large hourly step changes, and MISO and the interconnected regions are the least likely. For clarity, the curve shows only positive step changes; the negative portion of the curve is roughly symmetrical.

Table S4: Correlation coefficients between 2009 (2008) hourly wind power outputs.

	BPA	CAISO	ERCOT	MISO
BPA	1	0.32	0.04 (0.16)	−0.06 (−0.07)
CAISO		1	0.02	−0.23
ERCOT			1	0.24 (0.25)
MISO				1

and Y. Negative correlation between wind power output of two regions indicates that connecting the regions could result in a smoother supply of wind power, if the variations tend to be out of phase.

Table S4 shows correlation coefficients for wind power output data from 2009 (and 2008 if available). Figure S3 shows pairwise correlation coefficients plotted against the distance between the centroids of the wind plants of each region. All correlation coefficients are different from zero at the 1 % significance level and are highly significantly different from −1, the value for perfect smoothing. BPA paired with CAISO and ERCOT paired with MISO showed the strongest positive correlation, likely because fronts generally pass from west to east, creating similar conditions along north-south axes. CAISO and MISO showed the strongest negative correlation. Nevertheless, connection of the two regions did not result in smoothing of PSDs at frequencies above 24 h^{-1}, even when CAISO wind power output was scaled to simulate the same installed capacity as MISO.

The correlations are plotted with curves from Giebel (2000), derived from simulated European wind power data from sites up to 4,500 km apart, and Katzenstein et al. (2010), derived from wind power output from 21 Texas wind plants up to 500 km apart. Each time series consists of one year of hourly data (although that of Giebel (2000) is linearly interpolated from three-hourly data). Compared with pairwise correlations from European wind sites, BPA+CAISO and ERCOT+MISO are more highly correlated than average but well within the scatter of European data, while CAISO+MISO is an outlier compared with European data. The exponential fit for all pairs of ERCOT wind farms did not have the benefit of longer-distance data (Katzenstein et al. 2010), possibly explaining its difference from the European curve.

S1.6 Cost comparison with natural gas combustion turbines

We wish to evaluate the cost-effectiveness of interconnecting wind plants to smooth power output. BPA and ERCOT are the regions with the most volatile wind power output, and the correlation coefficient between them is low (see Table S4). We perform a coarse calculation of the cost of mitigating their 99$^{\text{th}}$ percentile negative step changes with a

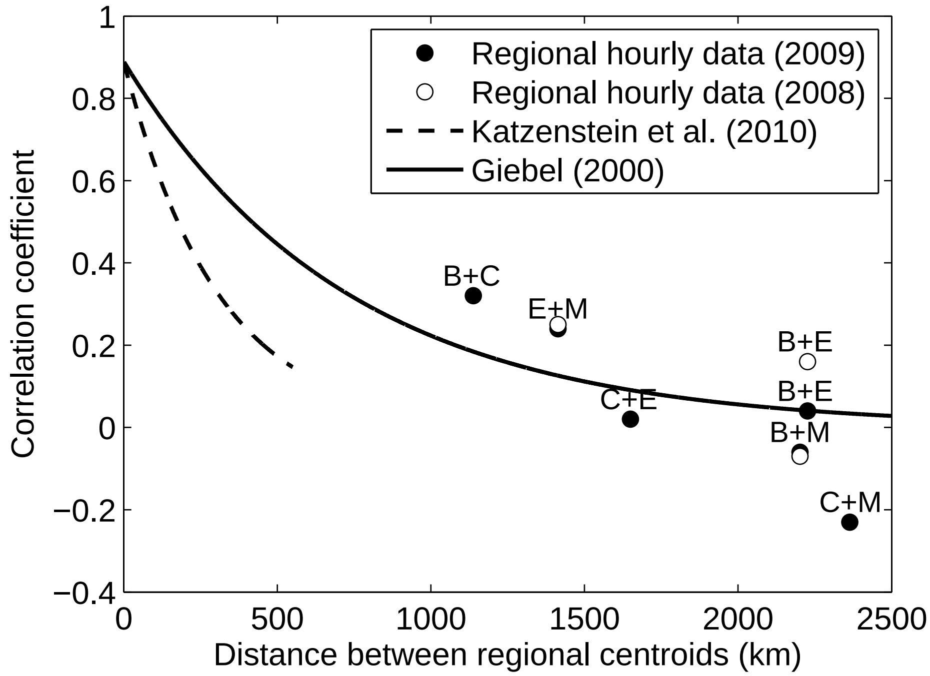

Figure S3: Pairwise correlation coefficients between regional wind power outputs tends to decrease as a function of distance between regional wind plant centroids. Pairs of regions are denoted by the first letters of their acronyms separated by the symbol +. Compared with European data, CAISO and MISO wind power is exceptionally anticorrelated, while correlation coefficients for the other pairs of regions fall within the spread of European data.

peaking natural gas plant and generating the extra baseload power that the connected regions could provide with a natural gas combined cycle plant. We then calculate the approximate length of transmission with cost equivalent to that of the extra generation capacity and compare this length with the actual distances between regions.

The 99^{th} percentile negative hourly step change in 2009 for both BPA and ERCOT wind power output was equal to 14 % of regional installed capacity, or about 300 MW and 1.2 GW respectively. We assume that a simple cycle gas plant is built to balance the step changes and that its overnight capital cost is \$1000/kW, fixed operating and maintenance (O&M) is \$7/kWh·yr, and variable O&M is \$15/MWh (EIA 2010). With 100 h/yr of operation, and amortizing costs with a 10 % discount rate over a 40-year lifetime, the total cost of the gas plant would be \$330 million for BPA and \$1.3 billion for ERCOT, for a total cost of \$1.6 billion. (The O&M costs contribute less than 10 % to the total cost.)

The amount of wind capacity available 92 % of the time is 340 MW in ERCOT, almost none in BPA, and 630 MW in the combined regions. Connecting BPA and ERCOT could therefore replace about 300 MW of baseload capacity. If this baseload capacity were provided by a natural gas combined cycle plant, it would cost \$430 million (using median cost estimates from Lazard (2011)). The total cost of the baseload and peaker gas plants in the absence of interconnection is therefore approximately \$2 billion.

The weighted-average criteria-air-pollutant damages from natural gas plants amount to \$0.36/MWh and the mean carbon emissions from a gas plant are 0.5 tCO_2/MWh (NAS 2010). With a carbon price of \$50/tCO_2, the total cost of the gas turbines becomes \$2.6 billion.

Depending on factors such as terrain, right-of-way costs, and permitting requirements, 765 kV single circuit transmission tends to cost between \$2.7 million and \$4.1 million (2010 USD) per mile (AEP 2008). At these transmission costs, building a gas turbine to mitigate 99^{th} percentile step changes would have capital cost equivalent to high-voltage transmission of length 490-740 miles (630 to 960 miles if criteria air pollutants and CO_2 costs are included). The geographic centroid of wind plants in BPA is separated from that of ERCOT by 1400 miles (the centroid of BPA wind plants is 750 miles from that of its nearest neighbor, CAISO, and the centroid of ERCOT wind plants is 850 miles away from that of its nearest neighbor, MISO.)

Reversing the calculation, the total cost of an ERCOT-BPA transmission line would need to be less than \$1.4 million per mile (\$1.9 million if emissions damages are included) to make the transmission line more cost-effective than gas plants to compensate for the extreme step changes and provide additional base load power. While transmission costs this low have been reported for flat exurban regions, costs over 1400 miles are likely to be higher.

Since the transmission distances with equivalent cost to the gas turbines are low compared with the distances between regions, this first-order analysis suggests that local gas plants would be a more cost-effective means of mitigating extreme negative step changes and providing extra baseload capacity than interconnection with high-voltage transmission. This analysis neglects the fact that the two individual regions with extra gas capacity would produce more energy than the interconnected regions; accounting for this would further reduce the calculated cost effectiveness of building transmission to mitigate wind variability.

We do not attempt to quantify other benefits of increased transmission capacity such as alleviation congestion or bolstering system reliability independent of wind power smoothing. We also do not quantify the possible disadvantages of interconnection between regions, such as the spreading of faults and the difficulty of coordination between markets (Cepeda et al. 2008). Further, the reliability benefit of increased wind-load transmission capacity has been shown to exhibit decreasing marginal benefit, such that economically optimal interconnection capacity is likely lower than installed wind capacity (Karki & Patel 2005).

We propose that incorporating the cost of extra transmission capacity to balance wind is important even though the existing high-voltage transmission network contains extensive interconnections between the regions examined in this paper. The Pacific DC Intertie (Path 65), for example, connects the wind-rich area of BPA to southern California. This path was found to be one of the most heavily used in 2007, and was operating at more than 75 % of capacity at a frequency of 18 % in the spring, 23 % in the winter, and 32 % in the summer (DOE 2009). Given this heavy usage, the path is unlikely to have sufficient excess capacity to allow the wind power output of BPA and CAISO to balance each other to the extent modeled in this paper. Incorporating the cost of excess transmission capacity is therefore a requisite element of an economic analysis of wind power smoothing due to geographic diversity.

S2 Net load

Like wind, electricity load is variable across a broad range of frequencies. Along with predictable daily and weekly periodicity, higher frequency, less predictable fluctuations present challenges to grid operators in maintaining system balance. Analysis in both the time and frequency domains can yield insight into load variability and the effect of wind power on the net load fluctuations which other generators must match. Apt (2007) found that the power spectra of wind and load were similar at frequencies between $(1\ \mathrm{h})^{-1}$ and $(5\ \mathrm{min})^{-1}$, providing a theoretical basis for the practice of treating wind as negative load at

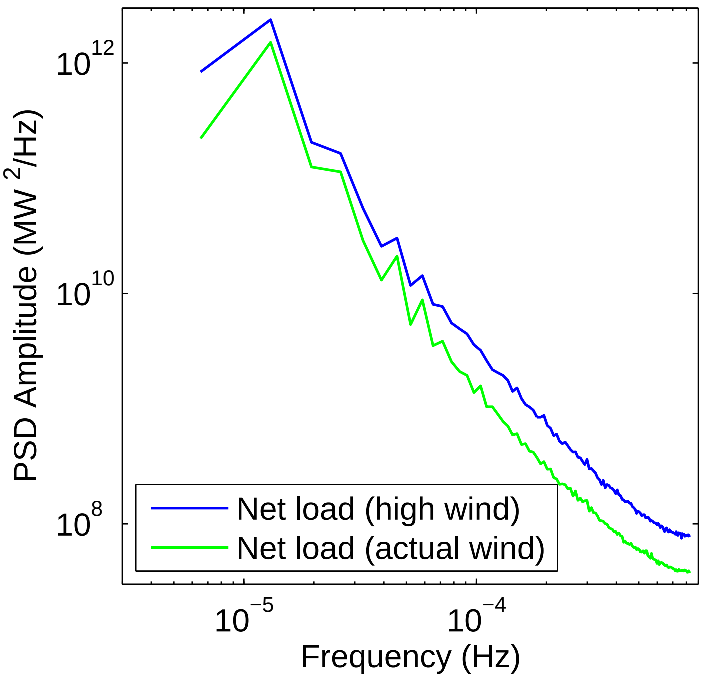

Figure S4: PSDs of 2010 CAISO net load with historical wind power output and wind power output amplified by a factor of 10. Increased wind capacity raises net load variability evenly across frequencies. PSDs are calculated with 16 averaging segments.

these timescales.

S2.1 Frequency domain

Comparing the PSDs of load and net load (load minus wind) reveals the effect of wind power on the variability characteristics of load across a range of frequencies. For current wind power penetrations in each region, net load has a PSD identical to that of load. To examine the effect of increased wind capacity, the PSDs of CAISO ten-minute net load for 2010 were calculated with both historical wind power output and wind power output multiplied by 10. Figure S4 shows that amplified wind power output translates the PSD upward in log-log space; that is, variability is introduced consistently at all frequencies such that the ratio between spectral power at any two frequencies is preserved. This result suggests that if wind capacity is substantially increased, more balancing and regulation resources will be required, but in the same proportion of slow-ramping to fast-ramping resources as currently.

Table S5: Wind-load correlation coefficients for 2009 (2008) hourly data.

Region	ρ(wind, load)
BPA	−0.16 (0.00)
CAISO	0.03
ERCOT	−0.28 (−0.18)
MISO	−0.08
BPA and CAISO	−0.02
BPA and ERCOT	−0.21 (0.00)
BPA and MISO	−0.12
CAISO and ERCOT	−0.22
CAISO and MISO	−0.24
ERCOT and MISO	−0.29
BPA, CAISO, and ERCOT	−0.17
BPA, CAISO, and MISO	−0.22
BPA, ERCOT, and MISO	−0.27
CAISO, ERCOT, and MISO	−0.32
BPA, CAISO, ERCOT, and MISO	−0.30

S2.2 Step-change analysis

Step-changes in net load, when compared with those in load, show the effect of wind power on the ramping requirements placed on the remainder of the generation portfolio. At current penetrations, wind causes increases in maximum and mean net load step changes of less than 1 % (with the exception of BPA maximum step changes, which increase by less than 3 %). To characterize the effect of expanded wind capacity on net load step changes, wind power output time series were scaled such that wind power fulfilled 50 % of load. Under the high-wind scenario, interconnection mitigated maximum hourly step changes: positive (negative) step changes for the individual regions ranged from 13 to 20 % (15 to 36 %) of total load whereas maximum positive and negative step changes for the aggregated regions were only 11 %. Interconnection had no effect on mean step changes, which consistently rose by 2 % due to the expansion of wind power capacity.

S2.3 Correlation analysis

Table S5 shows correlation coefficients between wind and load for each region and the aggregated regions. For 2009 data, ERCOT had the strongest anticorrelation between wind and load followed by BPA, and MISO and CAISO had near-zero correlation. Anticorrelation between wind and load could exacerbate net load variability as wind power capacity is increased, placing greater demands on balancing and regulation resources. Further, wind power that is anticorrelated with load will tend to displace baseload generators, which are the marginal plants during times of low load, rather than peak load generators, which are more expensive but easier to ramp. Displacing coal base load may also provide greater reductions in greenhouse gas emissions than displacing load-following resources. Connecting regions does not raise the correlation between wind and load; for most pairs of regions, the correlation coefficient for the summed data is between those for the individual regions, and connecting CAISO and MISO results in a correlation coefficient substantially less than that of either region (2009 data). Interconnecting all four regions results in lower wind-load correlation than in any of the individual regions. Like the frequency domain and step change analyses, the wind-load correlations show that interconnection may not mitigate the negative effects of wind power variability on the remainder of the system.

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