CEE 289 Project

Stochastic Properties of (Simulated) Wind Speed: Variability in the Time and Frequency Domain

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1. MOTIVATION

As wind power becomes integrated into a more substantial portion of the electric power system, wind professionals face a challenge that is inherent in this renewable energy source - the variability in wind speed. Wind flows from high to low pressure areas, caused respectively by low and high temperature systems. While the daily and the seasonal temperature cycle, due to the earth's self-rotation and its revolution around the sun, affects most part of the world (besides equatorial regions), wind remains highly stochastic. After all, temperature differences are caused as much by predictable planetary motions as by highly variant atmospheric and oceanic conditions. For instance, overcast slows down the dissipation of warm temperature from the ground after dusk, El Nino keeps global temperature high, and storms could last for a wide range of time intervals. The interactions of these conditions render wind a non-stationary stochastic process even from the yearly window point of view.

At a higher penetration into the power system, wind's stochasticity has a greater influence on the overall power supply's variability. Further, conversion from wind speed to electric power is probabilistic, and electric power demand is stochastic. Due to these uncertainties, maintaining a steady stream of power supply to match power demand becomes a challenge. Nonetheless, wind has significant advantages, from being a clean and renewable energy source. Consequently, there has been an increasing number of integration studies exploring the possibility of incorporating more wind power into the electric grid [1] to [5]. These integration studies focus particularly on intra-diurnal wind power variabilities (i.e. between period of 24 hours and roughly 20 minutes), because (1) wind experiences substantial step changes within a day, and because (2) variations at longer time intervals are cased by climate variations that affect much larger regions, and thus a majority of wind farms at once.

2. GOAL

This study aims to understand some of the challenges in wind integration. In particular, it aims to examine some of the variabilities in wind, and the potential in variability reduction through increasing the number of wind turbines, and through diversifying wind turbines' geographic locations. Ideally, this study would focus on the variability in the differences between power demand and wind power supply (Appendix B, figure.B1); constricted by available data, however, only wind speed will be examined.

3. DATASET

The wind speed data used in this study comes from the National Renewable Energy Laboratory's (NREL) "Western Wind and Solar Integration Study" [1]. The dataset consists of wind speed time series from 2004 to 2006, at 10-minute resolution and for 32,043 wind turbine sites in the Western United States (figure.1). These wind speed time series are simulated from regenerating historical atmospheric interactions using Numerical Weather Prediction (NWP) model at sites deemed potential for future wind farms. The reason for simulating a dataset is a lack of historical records at high spatial resolution. In short, these simulated data are not meant for accuracy, but are sufficient for a temporal and spatial overview of wind [1].

This study involves 25 wind turbine sites with varying spatial distances from a base site; all sites are picked arbitrarily, and the base site is site 17303 around the Wyoming and Colorado region (figure.1 and table.1). All three years worth of data at each site are used.

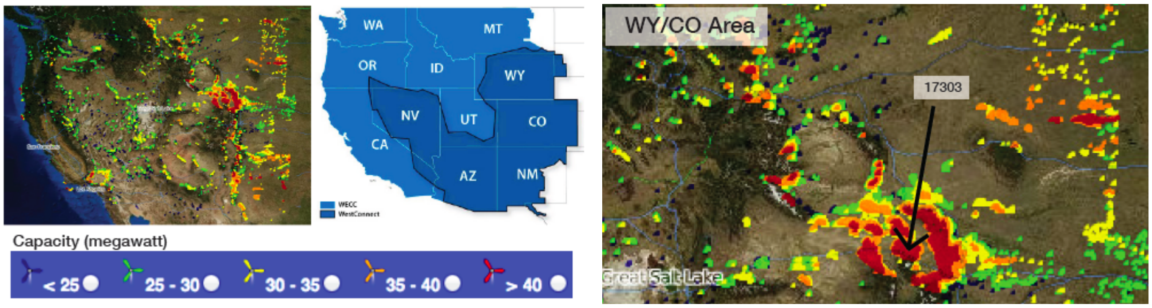


figure.1: Study area; the color gradient represents the max power output of each potential wind turbine site (image source: NREL)

Site Num	ID	Distance From 17303 (km)	Site Num	ID	Distance From 17303 (km)	Site Num	ID	Distance From 17303 (km)
1	17303	0.00						
2	17304	0.9	10	21395	82.1	18	12587	185.2
3	17302	1.7	11	16179	86.2	19	12027	218.1
4	17172	2.2	12	16589	91.2	20	24834	224.6
5	17422	2.2	13	13776	93.7	21	23293	232.3
6	16091	18.9	14	20454	127.6	22	15353	294.8
7	17404	25.7	15	13103	131.1	23	24591	340.1
8	18931	25.8	16	18471	146.1	24	9099	459.9
9	17445	35.1	17	23859	159.4	25	25941	522.1

table.1: The 25 chosen sites, sorted by their respective separation distance from base site 17303.

4. METHOD

This study measures the reduction in wind speed variability using a time-domain method, as well as a frequency-domain method. As the results will illustrate, diversifying the geographic locations of a portfolio of wind turbines reduces the portfolio's variability if measured with the time-domain method, but not if measured with the frequency-domain method. This report addresses the possible drawbacks in the time-domain method, and shows that increasing the number wind turbines in a portfolio potentially reduces wind variability more than diversifying these wind turbine's locations. The study procedure is as follows:

i. Study the wind characteristics in the time domain, focusing on the base site 17303.

ii. Confirm the time domain results in the frequency domain (using power spectral density, PSD), at site 17303.

iii. Study the spatial diversity's effect on wind variability with the time-domain method:

a. Compute the variance at the daily, monthly and three-yearly interval from 2004 to 2006 at site 17303, in order to look at how variance is dependent on interval size.

b. Compute the variance of the average wind speed between site 17303 and three separate sites: 21395 (82km away), 12587 (185km away), and 25941 (522km away). The goal is to see if increasing separation distance - hence increasing the spatial diversity of a two-site portfolio - will lower the portfolio's variance.

c. Build on part b by plotting the variance at the three-yearly interval between any two given sites in the 25 sites selection, against their respective separation distances.

d. Repeat part c, but separately for summer and for winter season. Summer is defined as between the 150th and 300th day of each year, and winter is the remainder. The seasonal cutoff date is from estimating the start and end of summer's lower wind speed variability (figure.2). Also, two-site comparisons at finer time intervals (i.e. daily and monthly) are not conducted, as seasonal comparison already hints at the time-domain method's limitations.

iv. Repeat step iii's part c, with the frequency-domain method:

a. The frequency-domain method only measures variances for frequency higher than daily: the focus is periods between 24 hours and roughly 20 minutes [5].

b. To measure the variance from PSD and for frequencies higher than daily, random vibrations concepts are used. Firstly, given a stationary process, the area under the PSD is the mean-square of the stochastic process (1). Secondly, given a zero-mean process, the mean-square of the stochastic process is also its variance (2). Then, the area under its PSD is the variance of the stochastic process (3).

$$E[X^2(t)] = 2\int_0^{\infty} S_{XX}(w)dw \tag{1}$$

$$E[X^2(t)] = \sigma_X^2(t) - \mu_X^2(t) = \sigma_X^2(t) - 0 = \sigma_X^2(t) \tag{2}$$

$$\sigma_X^2(t) = 2\int_0^{\infty} S_{XX}(w)dw \tag{3}$$

c. Wind, of course, is not a stationary process. However, for periods smaller than daily, the process could be considered stationary, as the seasonal trend has a much larger period. Even then, wind is still not a zero-mean process, and thus the "variance" described in this report for PSD is not the variance of the stochastic process, but a pseudo variance used to compare between portfolios.

5. RESULTS DISCUSSION

i. Time Series Properties

This section focuses on the time series of 17303. 17303's entire time series from 2004 to 2006 shows that the summer seasons (between the 150th and 300th day) contain smaller wind speed fluctuations and a lower mean, compared to the winter season (figure.2). Zooming into a particular summer and winter week confirms that wind speed during winter days tend to have larger fluctuations, tough not necessarily fluctuating more frequently (figure.3).

The autocorrelation computed using the entire three-year time series shows a seasonal trend with a period of roughly a year (figure.4). The autocorrelation of three separate one-year time series shows that each year is different, suggesting that the process is non-stationary. Further, zooming into the first 10 days worth of time separation shows the diurnal cycle (figure.5).

Overall, the seasonal and diurnal trend is due to their respective source of temperature fluctuations: (1) earth's revolution around the sun, and (2) earth's rotation. The larger fluctuations during the winter seasons are because the ground heats up less during the day, and thus does not have as much heat to dissipate during the night to keep the atmosphere warm. This results in a larger temperature - and thus wind speed - gradient.

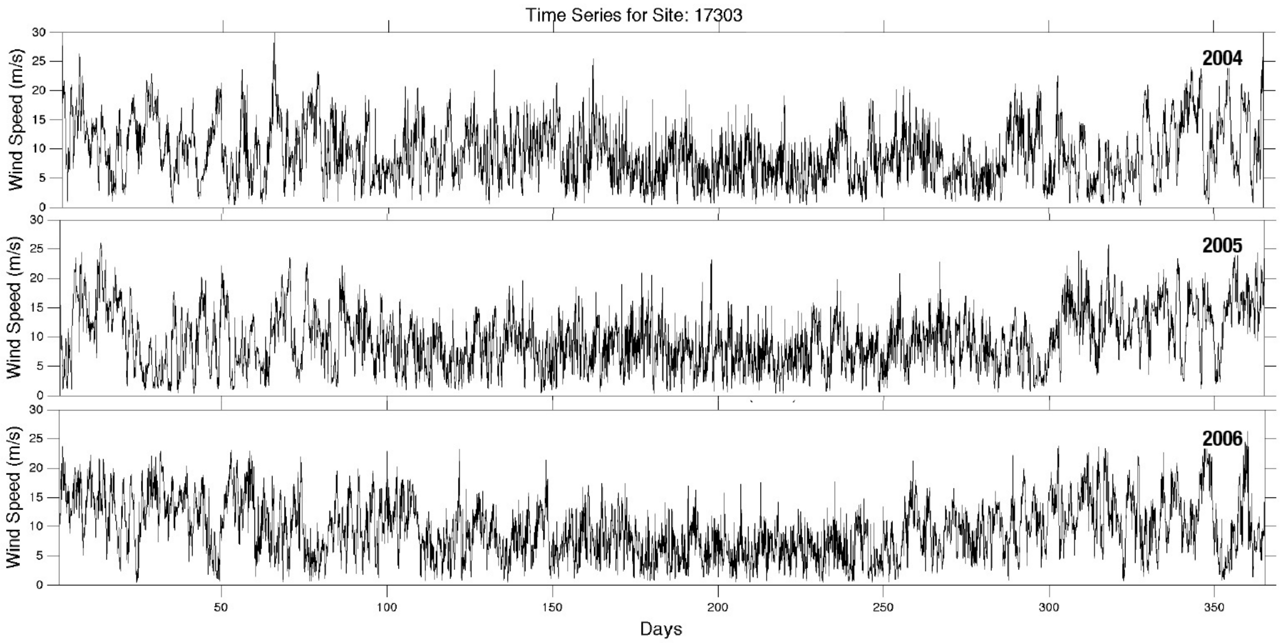


figure.2: Wind speed time series, X(t), for 2004, 05 and 06 (top, middle, bottom) at site 17303.

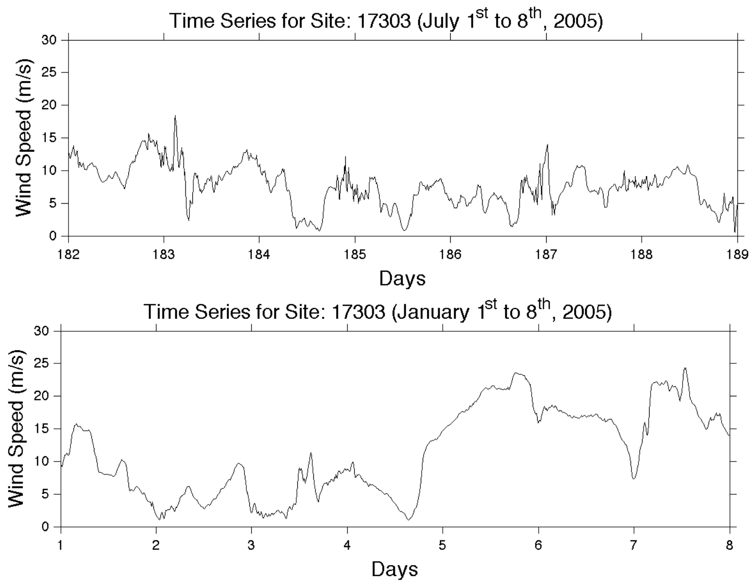


figure.3: Wind speed time series, X(t), for an arbitrarily selected summer week of 7/1-7/8/2005 (top), and for an arbitrarily selected winter week of 1/1-1/8/2005 (bottom) at 17303.

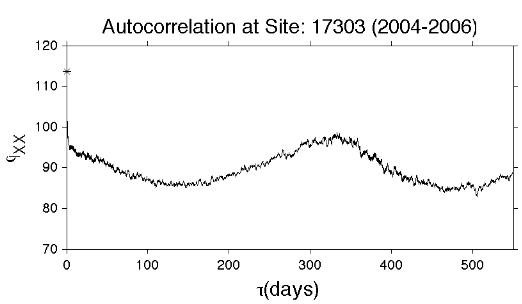


figure.4: Autocorrelation of the wind speed at site 17303, using the entire time series (i.e. 2004-06). The "*" on y-axis is $\phi_{XX}(\tau = 0)$, showcasing the immediate loss in correlation when time separation, τ, increases.

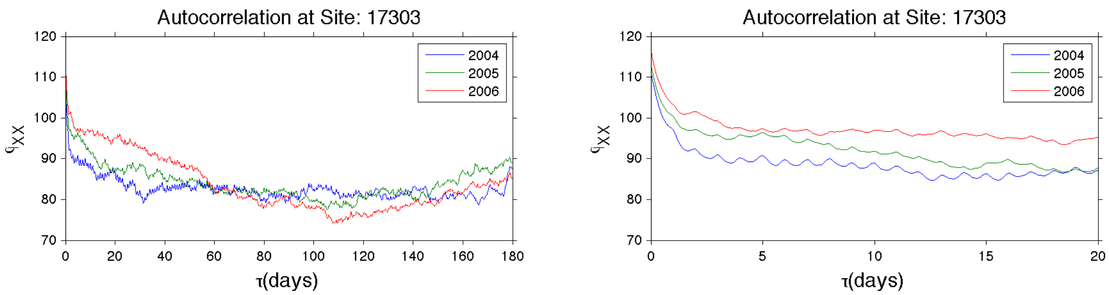


figure.5: Autocorrelation of the wind speed at site 17303, using 2004, 05 and 06 as three separate time series (left), and a view zooming into data with time separation less than 20 days (right).

ii. Power Spectral Density Properties

This section focuses on the frequency analysis of 17303. The PSD shows similar result as the autocorrelation - that there is a diurnal cycle (figure.6). (There also appears to be a 12hr cycle, but the reason for such is beyond the scope of this report). Further, it appears that wind is a narrow-band process for frequencies higher than roughly 0.5/day, but a relatively wide-band process for lower frequencies. This separation could mean: while there are many fluctuations with periods larger than a day (e.g. due to storms), the diurnal cycle is much more pronounced, compared to the intra-diurnal fluctuations. The goal of this report is to see what can reduce these intra-diurnal fluctuations.

Before conducting any variance reduction, this study break three-years worth of time series into six half-yearly signals, and then take the average of their Fourier amplitudes to compute the PSD. The result of this separation is a reduction in the width of the PSD, which translates to a reduction in the variabilities between discrete frequencies (figure.7). The upper bounds of these widths remains the same, which means this separation procedure has not reduced the area under the PSD, and thus the variance of the process. Lastly, the choice to break the signal into six is that there appears to be a half-yearly cycle (the reasons for such is also beyond the scope of this report). This study will continue to use PSD that is the average of six half-yearly signal.

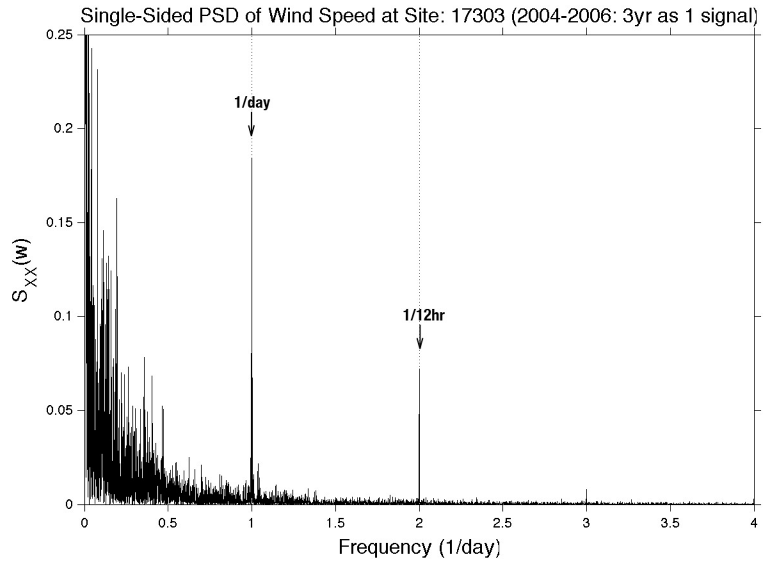


figure.6: Power spectral density (PSD) of the wind speed at site 17303, using the entire time series (i.e. 2004-06).

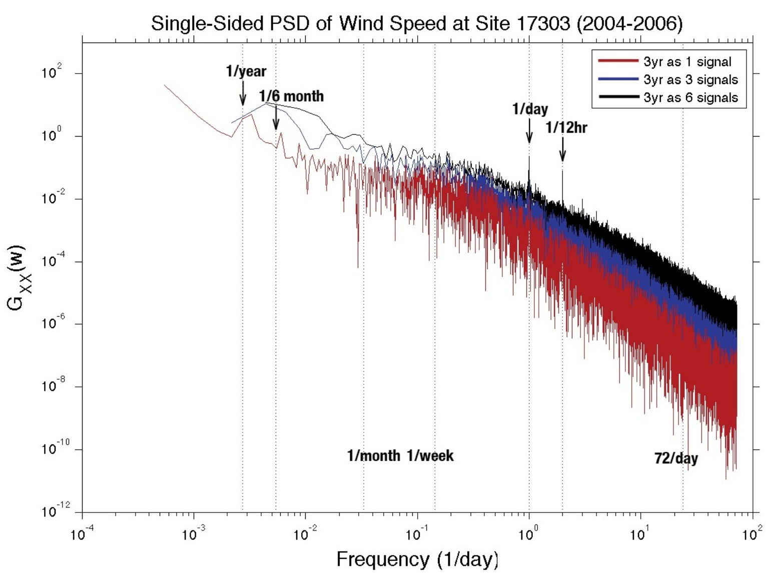


figure.7: Power spectral density (PSD) of the wind speed at site 17303, in log-log scale and using the entire time series (i.e. 2004-06), as (1) a single three-yearly signal, (2) as a combination of three one-yearly signal, and (3) as a combination of six half-yearly signal.

iii. Variability from the Time Series Point of View

The three-yearly variance of the averaged time series between any given two sites decreases as their separation distance increases (figure.8). However, if the three-year time series is separated into summer and winter, there appears to be more decrease for winter, and little decrease for summer (figure.9). (Note that a linear regression is likely not the best form of a fitted curve for this case, but is plotted to show the macro-relationship).

The difference between winter and summer implies that, for many days, there are little variance reduction with increasing separation distance, and that the overall trend towards the variance reduction is over weighted by the larger fluctuations - and hence the larger reductions - during the winter. Further, variance computed on the time domain at any scale assumes an ergodic process: the variance is merely the spread around a mean, without considering the timing of the spread. Yet, these variations' position in time is important because intra-diurnal variations are what energy professionals care most about. Variance measured in the frequency-domain should resolve this problem.

An example: Appendix B's figure.B3 shows two time series realizations during a day, with the same daily variance. One is a large downward trend, perhaps due to the passing of a storm: because such event would affect a large geographic area, there is little that portfolio diversification can do to prevent its effect. The other contains the same values, but arranged differently within a day: these smaller scale variations could be reduced with profile diversification.

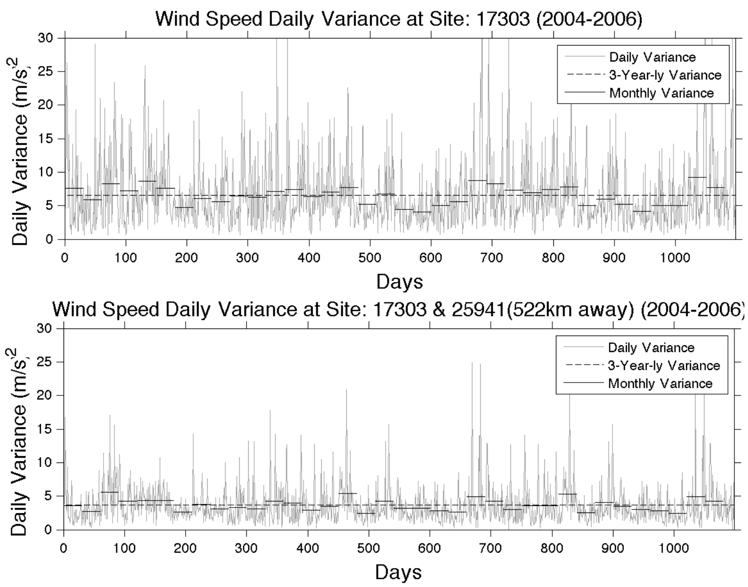


figure.8: Time domain variance for site 17303 alone (top), and for the average between site 17303 and 25941 - the furthest site from 17303, with separation distance of 522km (bottom). The variances measured is at three discrete time interval sizes: (1) daily, (2) monthly, and (3) three-yearly. (figure.B1 shows two other sites with intermediate separation distance).

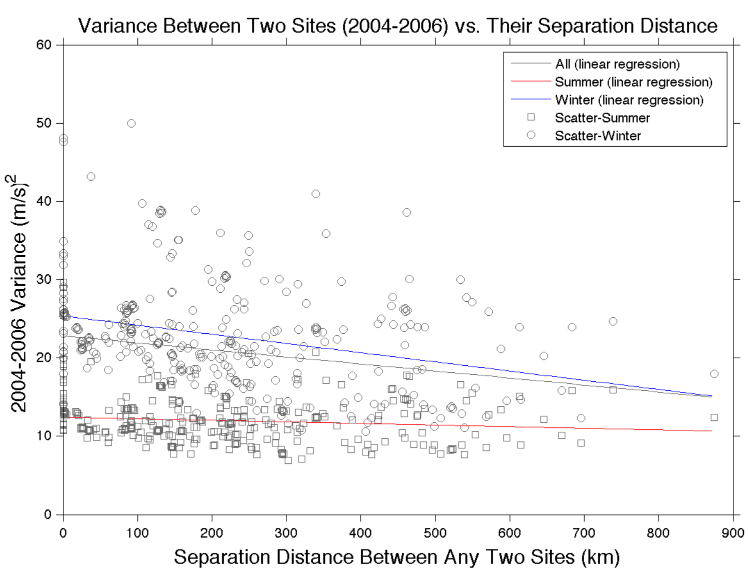


figure.9: The linear regression of the time domain variances for the average between any given two sites in the 25 sites set, measured (1) at the three-yearly interval, (2) only for the summer season, and (3) only for the winter season. Summer season is defined as between the 150th and 300th day of each year; winter season is the remainder.

iv. Variability from the Power Spectral Density Point of View

The variances measured from the frequency-domain conveys a similar message as previously hinted by the time-domain's summer variances - that there is no variance reduction in a two-site portfolio with increasing separation distance (figure.10).

However, the frequency-domain does indicate that by increasing the number of sites within a portfolio, the variance decreases (figure.11). Figure.11 is computed by including 8, 16 and 25 sites closest to 17303. As opposed to figure.7, figure.11 shows the PSD band beyond the one-day frequency lowering, which means that the area under the PSD - and hence the stochastic process's variance - is lowering. Figure.12 shows similar results using three different sites as the base site (portfolio size is increased by adding additional sites closest to the base site first). All four trend shows an overall decrease in variance as the number of sites in the portfolio increases. (There is convergence to the same variance because there are only 25 sites used in this study, such that the four portfolios converge in content as the number of sites increase).

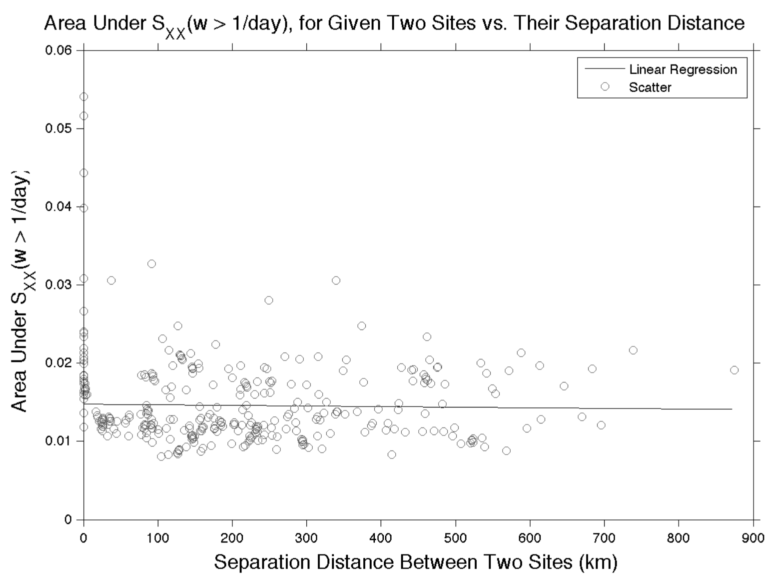


figure.10: The linear regression of the frequency domain variance (measured as the area under the PSD with frequency higher than once per day) between any given two sites in the 25 sites set.

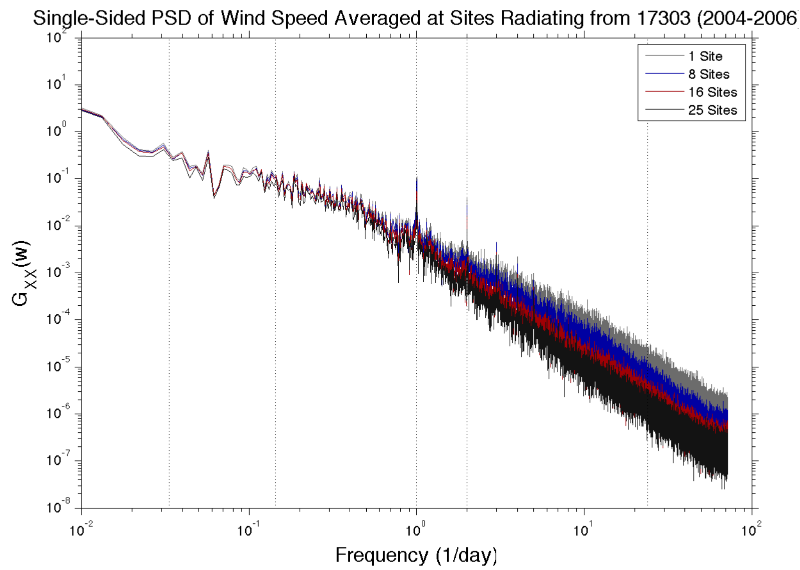


figure.11: Power spectral density (PSD) of the wind speed (1) at site 17303, (2) at 8 sites closest to 17303, (3) at 16 sites closest to 17303, and (4) at all 25 sites. The PSDs are in log-log scale and using the entire time series (i.e. 2004-06) as a combination of six half-yearly signal.

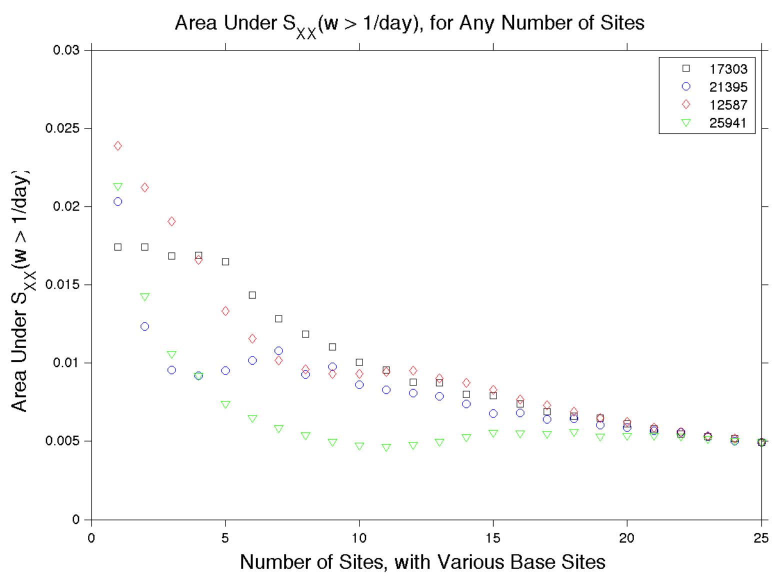


figure.12: The frequency domain variance at the number of sites closest to a base site; four base sites are chosen for display here: 17303, 21395, 12587, and 25941.

6. CONCLUSION

This study shows that increasing the number of sites within a portfolio of wind turbines seemly decreases the portfolio's overall variance, more so than increasing the separation distance between those wind turbines. Additionally, this study shows how analysis in the frequency domain potentially provides additional insights, especially if the focus is on a particular subset of frequencies. In this case, that focus is on frequencies higher than a daily occurrence.

Nonetheless, this study only used 25 sites - a minute number compared to the 32,043 available in Western United States. The next step for this study is to verify the claims made herein, with a much larger set of data. In particular, could figure.12. be replicated with any randomly selected 25 sites in Western USA After all, as figure.12 increases the number of sites, it is also increasing the separation distance between sites. Additionally, is there still a lack of variance reduction with separation distance, even for portfolios containing more than two sites? Although figure.10 shows a lack of variance reduction with separation distance, the claim is potentially valid only for a two-site portfolio.

A. Reference

[1] D. Lew, et al. "Wind Data Inputs for Regional Wind Integration Studies". NREL/CP-5500-50636. March. 2011.

[2] Michael Milligan, et al. "Assessment of Simulated Wind Data Requirements for Wind Integration Studies". IEEE. 2011.

[3] Cameron W. Potter, et al. "Wind Power Data for Grid Integration Studies" IEEE. 2007.

[4] Erik Ela, et al. "The Evolution of Wind Power Integration Studies- Past, Present, and Future". IEEE. 2009.

[5] Warren Katzenstein, et al. "The variability of interconnected wind plants". Energy Policy. March. 2010.

B. Additional Figures

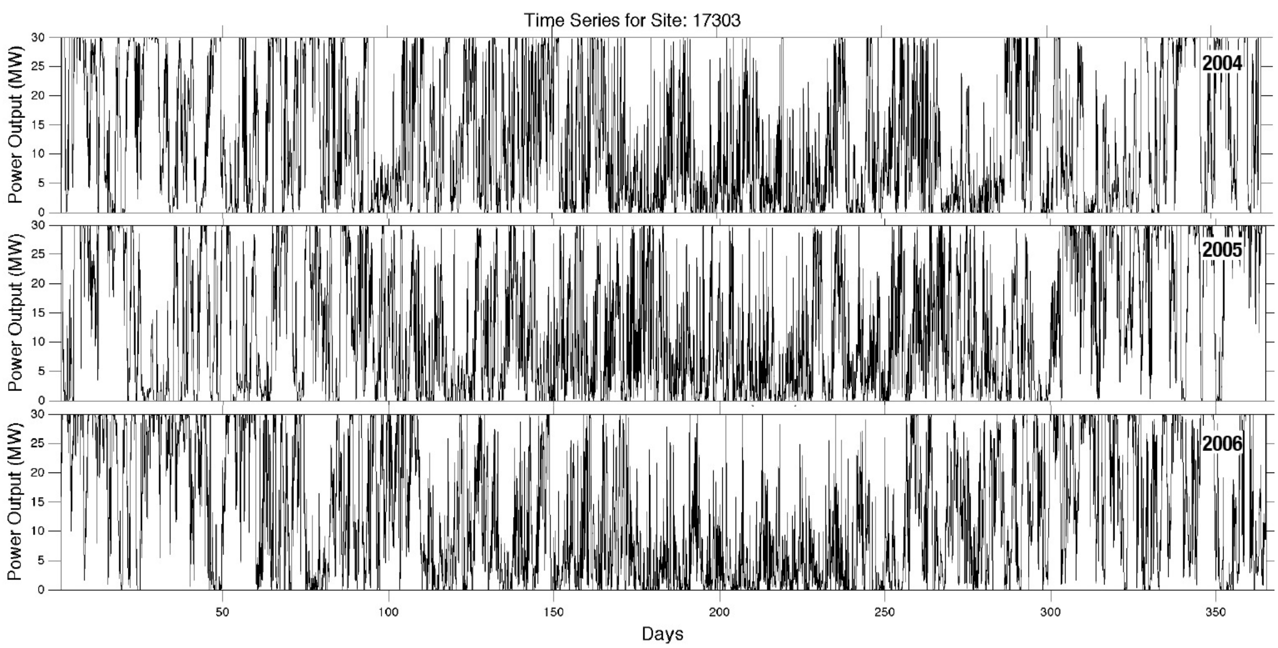
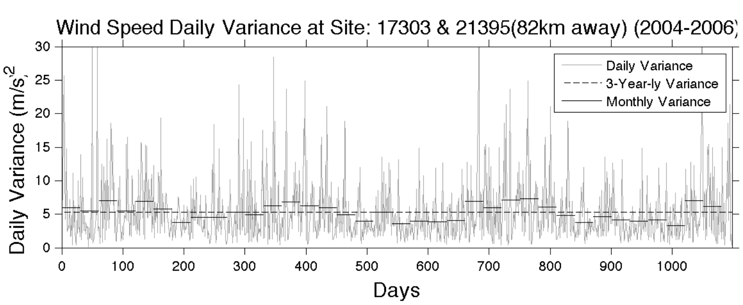


figure.B1: Power output time series for 2004, 05 and 06 (top, middle, bottom) at site 17303.



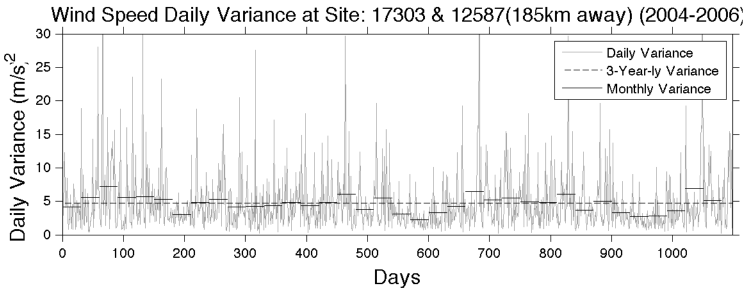


figure.B2: Variance measured in the time domain for the time series average between site 17303 and site 21395 (82km away), and that between site 17303 and site 12587 (185km away). The variances measured is at three discrete time interval sizes: (1) daily, (2) monthly, and (3) three-yearly.

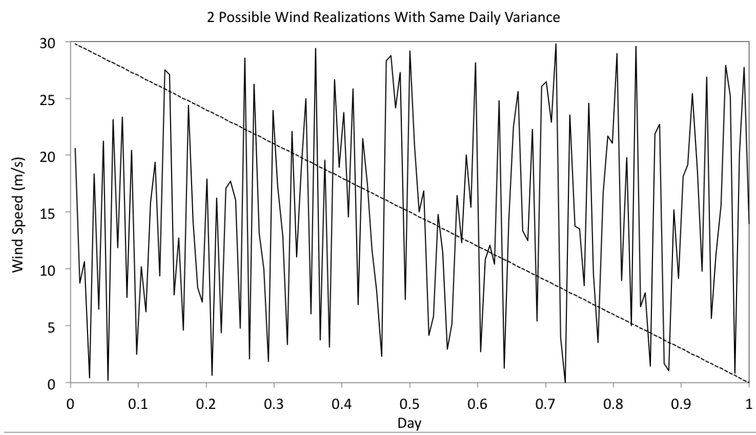


figure.B3: Two possible times series realizations that have the same variance within the given day: (1) a linear decrease from 30m/s to 0m/s at 10-minute interval, and (2) that linear decrease randomly sorted.