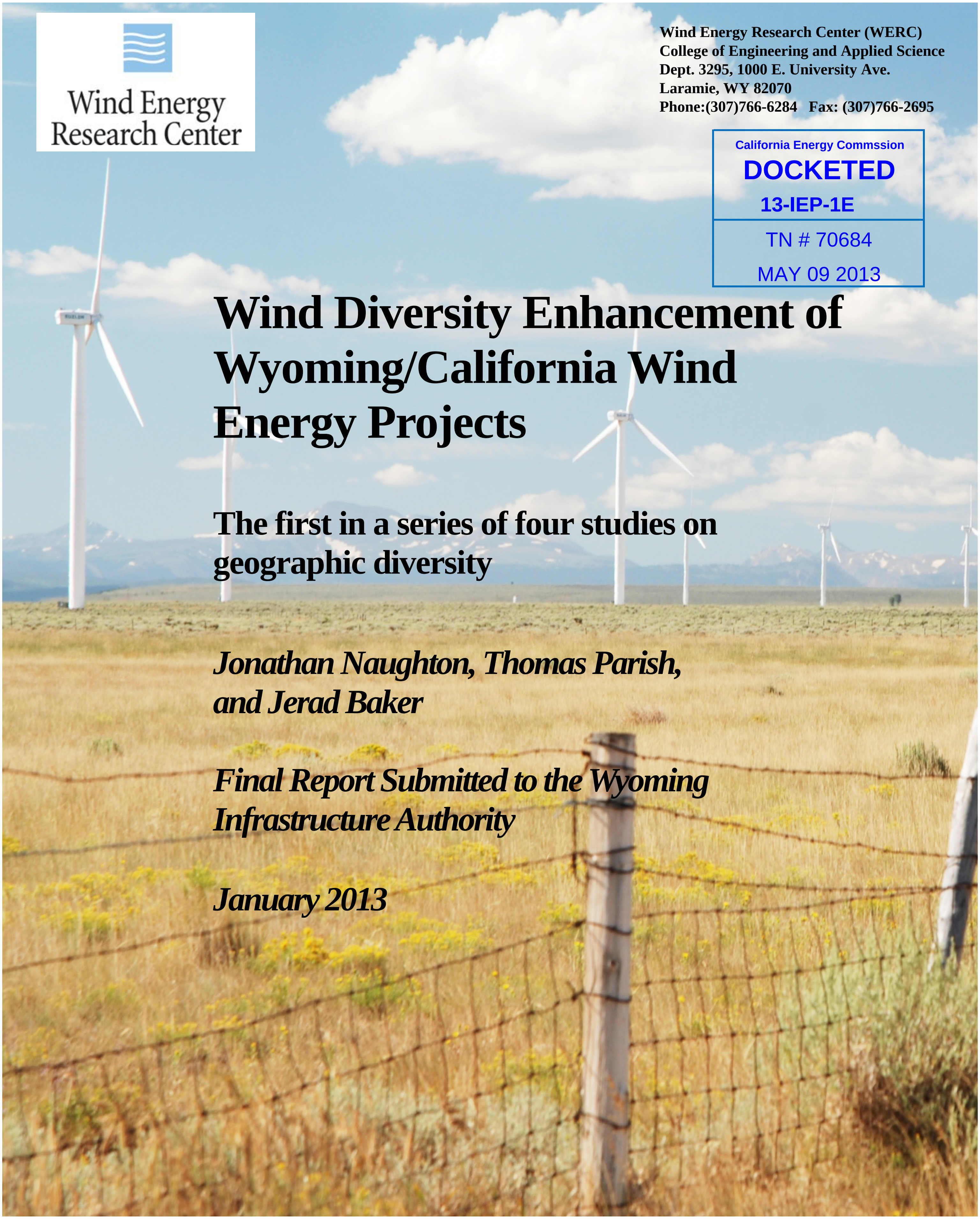


Wind Energy Research Center

Wind Energy Research Center (WERC)
College of Engineering and Applied Science
Dept. 3295, 1000 E. University Ave.
Laramie, WY 82070
Phone:(307)766-6284 Fax: (307)766-2695

Wind Diversity Enhancement of Wyoming/California Wind Energy Projects

The first in a series of four studies on geographic diversity

Jonathan Naughton, Thomas Parish, and Jerad Baker

Final Report Submitted to the Wyoming Infrastructure Authority

January 2013

The authors of this study would like to acknowledge the financial support provided by the Wyoming Infrastructure Authority. In addition, the support provided by Loyd Drain, Executive Director of the Wyoming Infrastructure Authority is gratefully acknowledged.

This report is the first in a series of four reports to compare the geographic diversity of Wyoming wind with wind resources

1. in California;
2. in Colorado;
3. in Nebraska; and
4. within Wyoming.

Executive Summary

Due to its outstanding wind resources, the economic benefits of developing Wyoming generated wind power for export to other states have been considered many times. This report discusses an issue that has not received much attention to date – the importance of diversity in wind resources. This report specifically considers the diversity of Wyoming and California wind and the benefits that are realized in the combination of these two resources. A year of wind resource predicted by a weather forecasting model is used as input to the analysis. A general analysis first considers the diversity in large areas of both states, and then specific locations are investigated to show the benefits of combining the locations predicted to have both good and diverse resources. These analyses yield the following important results.

- The wind resources in Wyoming and California are complementary in that the winds are largely uncorrelated due to their large geographic separation.

- The diversity of the wind in the two states yields real-world benefits when specific Wyoming and California sites are combined.

    - Variability of the wind-generated power is reduced thus decreasing the large swings observed from single installations and simplifying the integration of wind into the grid.

    - Savings in the $100 million range each year from reduced payments for dispatchable power could be realized. Assuming the dispatchable power is from fossil fuels, reduction in greenhouse gases can also be realized.

    - Wind power from Wyoming can be available at critical times when California's wind is not and when the load on the California's electrical grid (CAISO) most requires it.

Definitions

Cross correlation	A measure of the similarity of the behavior of the resources at two locations. High values of the cross correlation can indicate similar behavior, whereas low values of the correlation can indicate different behavior.
Correlation coefficient	Normalized correlation. The correlation coefficient varies between 1 (high correlation) to 0 (no correlation).
Diurnal variations	Variation of a resource over a day (hourly variations)
Diversity	Resources that exhibit diversity are complementary. Resources at sites with little diversity behave similarly (high at the same time, low at the same time), whereas good diversity indicates little relationship between resources at different sites.
Geographical diversity	Diversity that arises from using two resources from different locations
Gross capacity factor	The amount of power predicted to be produced at a site (excluding down time and other losses) at a particular hub height relative to what would be produced were the turbine running at full output all the time
Hub height	The height of the center of the wind turbine rotor (or the hub) above ground level
Joint statistics	Statistics that involve two different locations
Makeup power	Alternate power used when wind power falls below what it is expected to supply
Power curve	The relationship between wind speed and output power for a specific turbine
Ramping event	Large rapid changes in wind-generated power output due to rapid increases or decreases in wind speed
Root mean square (rms)	A measure of the variability of power. The root mean square is equivalent to the standard deviation.
Seasonal variations	Variation of a resource with season
Wind power density	A measure of the wind resource (in Watts per square meter) at a particular site independent of the wind turbine to be used

Introduction

California is a leader in wind-produced electricity, but is also a large energy user. In contrast, Wyoming has some of the best wind resources in the world, but is already a net exporter of electricity. As a result, a number of studies indicate that providing electricity generated by Wyoming wind to California is beneficial to both States. Recently, 80m and 100 m wind maps developed by NREL in conjunction with AWS Truepower indicated that Wyoming has a significant amount of developable wind at a capacity factor of 45% or greater as shown in Figure 1.[1] Currently, the state of Wyoming has just over 1400 MW of installed wind capacity, and thus the State's wind resources can provide for significant expansion. Nine (9) of the Western States have a need for such resources due to Renewable Portfolio Standards (RPS). For example, California has a standard that requires their electric utilities to provide 20% of their retail sales from renewable energy by 2013 growing to 33% in 2020.[2] This alignment of wind resource and need is promising. California's RPS accounts for two-thirds of the renewable demand in the Western Interconnect. This alignment of wind resource and need is promising. A recent Western Electricity Coordinating Council (WECC) 10-year regional transmission study has indicated that locating 12,000 GWh of electricity production, or 13% of the electricity required under California's RPS, in Wyoming would result in a reduction in the annualized capital cost of ~$600 million per year.[3] The WECC study analyzed wind development in California and compared the economics to the development of wind in Montana, New Mexico and Wyoming. Wyoming's high quality wind resource resulted in the annual savings referenced above. Such savings over a 20 year period represent a net present value of over $9 billion dollars assuming a 5% interest rate.

Despite these economic advantages, wind adds the complexity of being a variable generation source dependent on the temporal variation of the winds. As wind energy continues to penetrate further into the electricity market, issues such as forecasting capability, backup generation and eventually grid-scale energy storage become critical to address. Identifying ways in which to mitigate the cost and to address operating issues associated with the variability of renewable energy on the grid was the catalyst that resulted in the commissioning of the current report.

An additional benefit of using resources from different geographical resources is the potential of reducing the effects of variability in the wind. Swings in electricity production by renewable resources are known as ramping events. So called wind diversity can lead to less volatile changes in energy output. At a given location, the variability of the wind arises from several sources including diurnal and seasonal variations. Aside from straight statistical measures, issues such as the passing of weather systems affect the exact temporal variations experienced at a wind site. Thus using energy produced from several different sites can smooth the variations as these time-dependent features will not happen at the same time at all sites. The reduction of ramping events from standalone wind farms can be particularly beneficial to Regional Transmission Operators (RTO), Balancing Authorities (BA) and the rate payers.

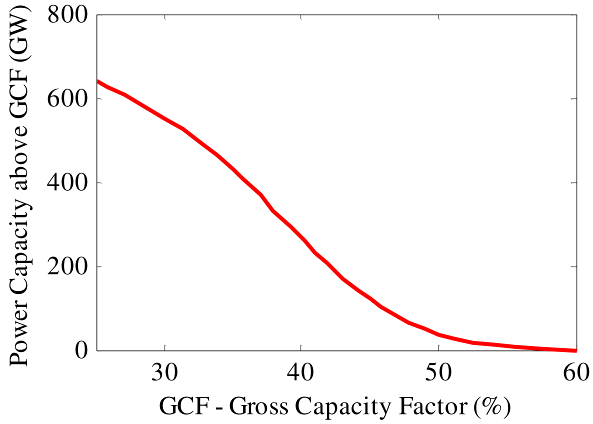


Figure 1 – Wind development potential in Wyoming at various gross capacity factors. A hub height of 80 m has been assumed. This figure has been adapted from reference 1.

The objective of this work is to perform an initial assessment of the effectiveness of combining California and Wyoming wind resources. Several sites are chosen for evaluation in Southeastern Wyoming and throughout California. Wind data at the sites are considered to quantify wind resource diversity, and demonstrations of the effectiveness of diversity are provided. The results indicate that, in addition to providing additional renewable resources, using geographically diverse sites can significantly decrease variability (i.e. ramping events). Thus, wind diversity is another benefit of using geographically disperse wind resources that may add to other benefits (such as cost of energy, resource availability and development issues) to assist with decisions on how to obtain the level of renewable energy desired. Given the proven economic benefits of Wyoming wind delivered to California, the diversity of the wind resource between the states provides additional reasons to consider combining renewable energy assets to meet renewable energy targets today and in the future.

Description of Wyoming and California Winds

A brief description of Wyoming and California winds is presented here. Southeast Wyoming winds are driven by the topography, elevation, and the weather conditions that result. Flow through the low point in the continental divide caused by pressure differences that set up across Wyoming in the winter cause that season to have the best wind resource. However, wind resource remains very good throughout the rest of the year, with a fairly significant decrease in winds in the late summer. See a companion report on Wyoming wind diversity for a more detailed discussion of Wyoming's wind.[4]

The wind resource in California is such that the higher quality winds are much more localized. The historical wind energy development locations are all located in passes that serve to funnel winds from one side of the mountains to the other. Low winds are typical of the winter, whereas the warmer weather associated with spring and summer draws cool coastal air inland toward the interior valleys and deserts.[5]

As is evident, the processes affecting the winds in Wyoming and California are significantly different, which should provide beneficial diversification should wind

plants at multiple sites in Wyoming be used to provide power for California. In addition, capacity factors exceeding 45% are expected at new installations located in Wyoming, whereas historical capacity factors at the better locations in California are in the 25-30% range.[6] These California capacity factors include both newer and older turbines, so it is not necessarily representative of the capacity factors that could be expected from new installations. Studies also suggest that technology improvements that increase net capacity factor for turbines operating in lower wind regimes will also increase the net capacity factors in windier areas by an equivalent amount.

Approach

Overview

To investigate the promise of wind diversity on wind energy power production, an initial investigation using data from a mesoscale weather forecasting model is carried out. One year of data for multiple sites in Wyoming and California is used. Monthly average wind speeds are investigated to characterize overall trends, whereas correlations between sites are used to estimate diversity. Finally, power production from a distribution of turbines over different combination of sites is determined. While not comprehensive in nature, these analyses clearly support the importance of wind diversification.

Locations Chosen

For this initial study, five locations in the wind producing areas in Southeastern Wyoming were selected for the analysis: sites near Rawlins (RSW), Casper (CNE), Medicine Bow (MBW), Southern Laramie Valley (LVS), and Wheatland/Chugwater (WC). These locations, shown in Figure 2, are regions of favorable wind resource near current wind plants or those proposed for development in the future. In California, three primary sites that are homes to current wind plants, Tehachapi Pass (TP), San Gorgonio Pass (SGP), and Altamont Pass (AP), were chosen for this analysis and are also shown in Figure 2.

Description of Data Sets

The data used for these studies were obtained from the Weather Research Forecast Model (WRF) run with a High Resolution Window (HRW) that provides 4 km horizontal spacing. The closest grid point in these data sets to the points identified in Figure 2 was used to provide wind information. The data used here were extracted from one of four WRF runs performed each day, and data were taken from the model for 24 hours past the start time. The next day's simulations were then used to continue the data from that point. One year of data was used starting in July 1, 2009 extending until June 30, 2010. For some periods of heavy forecasting use (e.g. the month of August), the solutions did not exist due to the need to use computational resources for other purposes (e.g. Hurricane modeling). Data extracted from the model were used to estimate hourly wind speeds at 80 m above the ground.

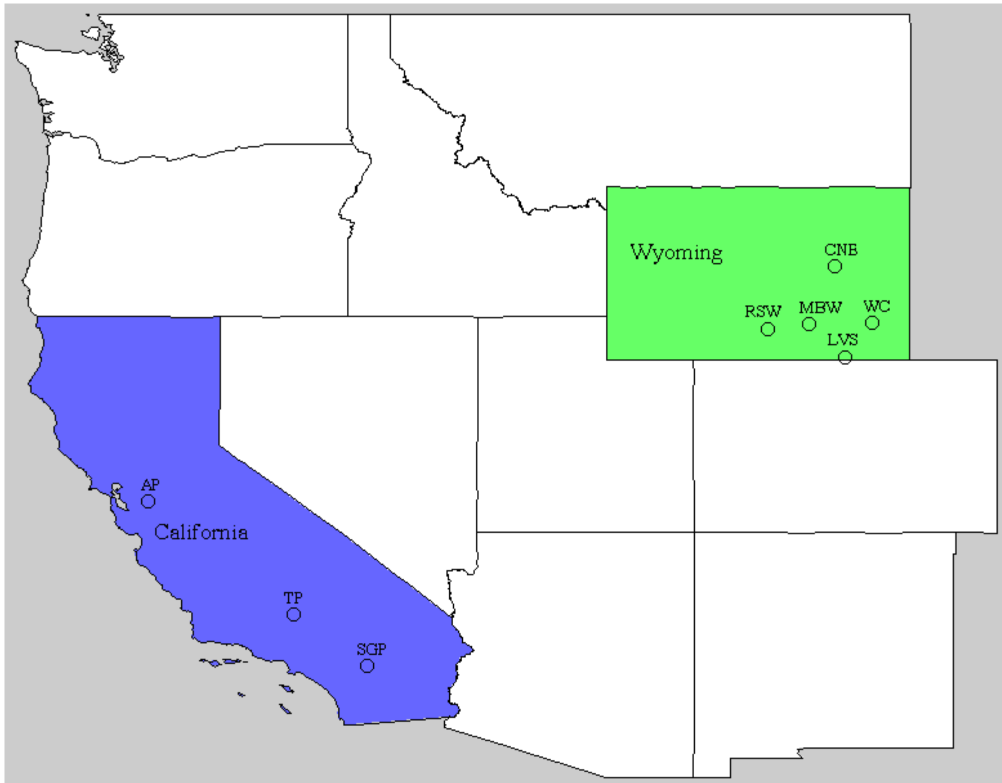


Figure 2- Wind sites selected for the Wyoming/California wind diversification study.

Analysis Performed

Several types of analysis were performed here to evaluate wind diversity. First the annual wind power densities (the average of the instantaneous wind power density $p = 1/2\rho u^3$, where ρ is the density and u is the instantaneous velocity at the height of interest) at 80 m above ground level were determined to locate likely sites for development and to provide an evaluation of the wind resource at locations of existing wind sites. Next, correlations were performed between specific sites in one state with sites in the region of interest in the other state. Using site pairs with promising correlations, monthly and diurnal wind speeds and power production estimates were all used to demonstrate the benefits of diversity. Determination of correlations and power production is discussed in more detail below.

Joint statistics between sites is the primary means used to quantify diversity. For this purpose, scatter plots of the wind power density at two locations were first considered. Such plots graphically depict the relationship between the winds at different times. To quantify this relationship, the cross correlation of the wind power density between the two sites $R_{p_1p_2}$ was calculated using

$$R_{p_1p_2} = \frac{1}{N}\sum_{i=1}^{N} p_i(x_1)p_i(x_2) \,,$$

and a corresponding cross correlation coefficient $\rho_{p_1p_2}$ was defined here as

$$\rho_{p_1p_2} = R_{p_1p_2}/(R_{p_1p_1}R_{p_2p_2})^{1/2} \,,$$

where p_1 and p_2 are the wind power density at the different sites identified by x_1 and x_2, and N is the number of wind power densities that are used in the determination of R. The first equation is equivalent to the cross-correlation function at zero time lag as defined in reference 7. When the correlation coefficient is one, the winds at the two locations follow each other exactly (perfectly correlated). When the correlation coefficient is zero, the winds at the two sites are uncorrelated, which is the desired case for wind diversity.

To demonstrate the beneficial effects of choosing sites with diverse wind, the combined power production of different sites was considered. The time history of production was considered as were the mean and variance of the power production for the year. The production was determined by choosing a wind turbine power curve (here the GE 1.5 XLE) and using the hourly wind data to determine instantaneous power. This instantaneous power was then integrated over time to determine energy production E,

$$E = \sum_{i=1}^{N} P(u_i)\Delta t,$$

where $P(u_i)$ is the wind turbine power at velocity u_i, Δt is the time between velocity samples (1 hour in this case), and N is the number of velocity samples used to determine E. The average power $\bar{P}$ could be determined using

$$\bar{P} = E / \sum_{i=1}^{N} \Delta t.$$

Results

The analysis processes described above were applied to wind data from Wyoming and California to assess the benefits of diversity. The wind power density determined from the data is first described followed by a discussion of the correlation results. Finally, evidence of the benefits of diversity is shown by choosing promising locations from the correlation results and determining the winds and resulting power produced at those sites.

Wind Power Density

Prior to performing correlations, it is important to ensure that the points used for the correlations are favorable sites for wind power production. The wind power density at 80 meters above ground provides a measure of the wind potential and is shown for Southeast Wyoming in Figure 3 and for California in Figure 4. Regions with wind power densities above 400 W/m^2 (pink) are considered likely to be good sites, whereas higher wind power densities (reds) would be considered to be excellent. Also shown in the figure are the sites chosen for analysis. It is clear in these figures that high quality wind resource is widespread in southeast Wyoming, whereas onshore locations with high quality wind are rather limited in California. All the sites in Southeast Wyoming chosen for further study are in regions of high quality wind (wind power density > 500 W/m^2), and the California sites at San Gorgonio and Tehachapi Pass are locations of better quality wind. Having ensured the quality of the wind at these locations, correlation analysis was undertaken.

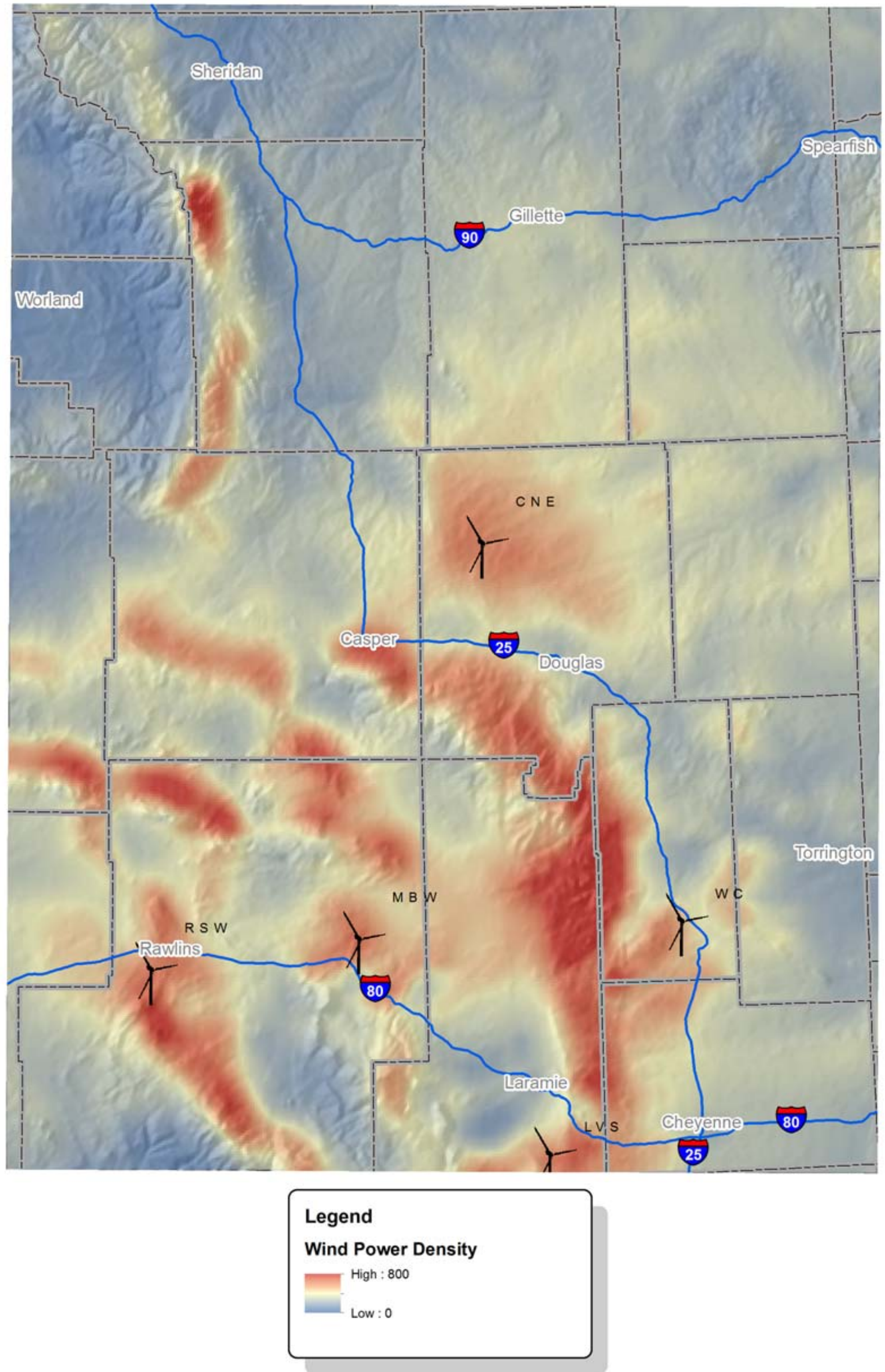


Figure 3- Wind power density (W/m^2) at 80 m above ground level in Eastern Wyoming. Note the outstanding resources throughout Southeast Wyoming.

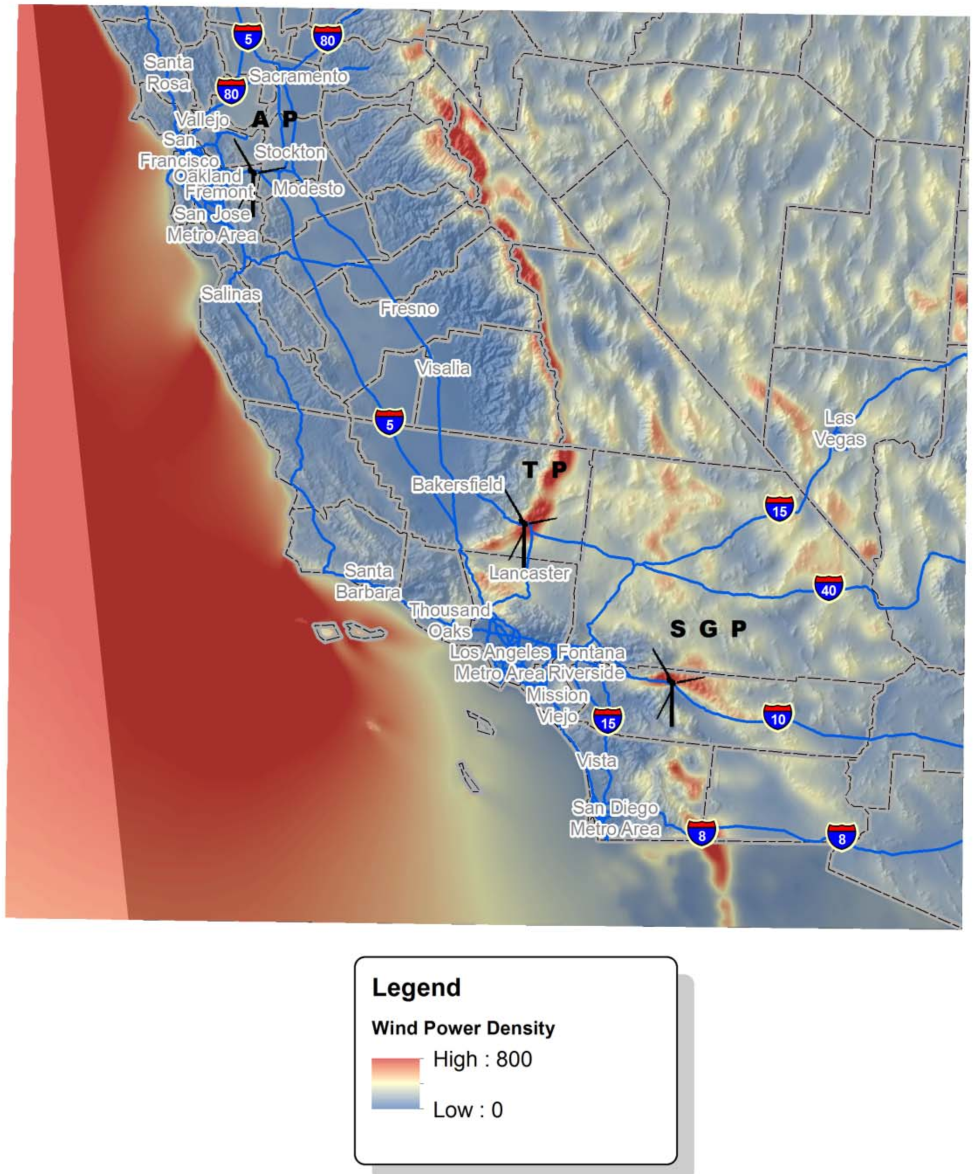
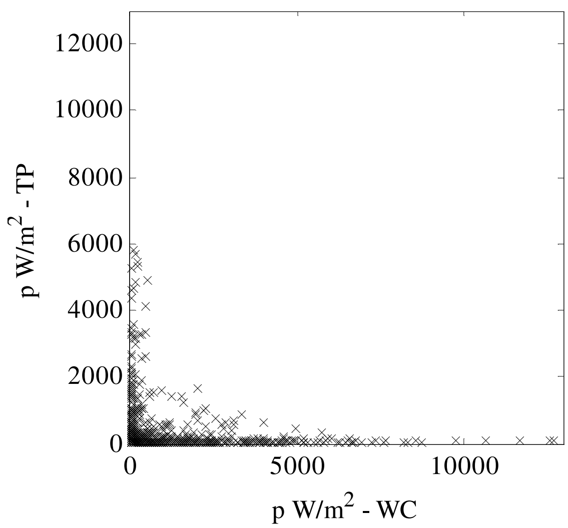


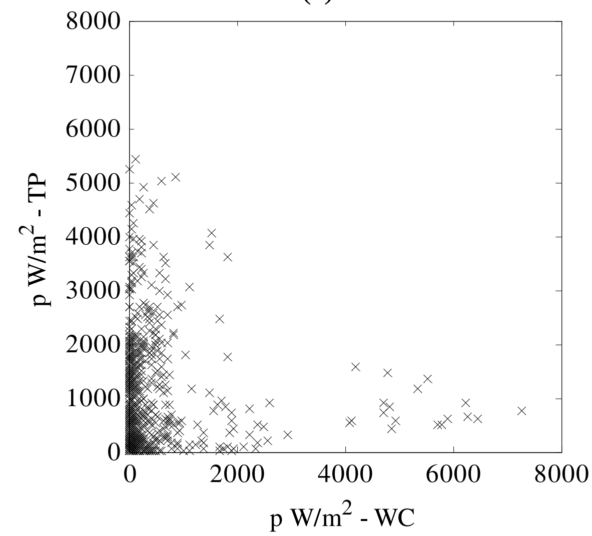
Figure 4 – Wind power density (W/m^2) at 80 m above ground level in California. The highest resources lie offshore, an area that was not considered for this study.

Correlations

The average wind power density provides an indication of good wind resource locations, but it does not provide any information about the potential diversity of two sites. To understand the concept of diversity and its relationship to correlations, consider Figure 5 that shows the instantaneous wind power densities at Wheatland/Chugwater and Tehachapi Pass plotted against each other for two different months. When winds are high at Wheatland/Chugwater and low at Tehachapi Pass, the points will appear along the horizontal axis. In contrast, points will appear along the vertical axis when winds are high at Tehachapi Pass and low at Wheatland/Chugwater. Cluster of points in the plots indicate likely combinations for the month plotted. As a result, the diversity of these two sites can be determined by considering the distribution of the points in Figure 5. During the winter (Figure 5(a)) the winds at Wheatland/Chugwater tend to be high while the winds at Tehachapi are lighter as indicated by points clustered along the x-axis. Nonetheless, there are times when Tehachapi is producing power when Wheatland/Chugwater has relatively low output as indicated by the smaller number of points near the y-axis. In contrast, Figure 5(b) shows higher winds in Tehachapi during the summer months when the winds at Rawlins are at a lower level. Since these plots differ significantly from highly correlated winds that would lie clustered around a line from the bottom left hand of the figure to the top right hand of the figure, low correlation and good diversity are expected for these two sites. By combining the output of these two locations, it should be possible to reduce the power variability by taking advantage of the apparent diversity of the two sites.



(a)



(b)

Figure 5 – Instantaneous relationship between wind power density at two sites (WC - Wheatland/Chugwater, WY and TP - Tehachapi, CA): (a) December 2009 and (b) May 2010. Cluster of points in these figures indicate likely wind power density combinations at the two sites for the month shown.

Although such analyses are useful on a case-by-case basis, they would be difficult to carry out for the many points needed to build an understanding of relationship, for instance, between a given point in Wyoming and all potential wind producing areas in California. The cross correlation coefficient $\rho_{p_1 p_2}$ provides a measure of the diversity. Values near unity indicate winds at two sites that tend to behave similarly (poor diversity), whereas lower values provide an indication that the winds behave differently (better diversity). Figure 6 shows the cross-correlation coefficient for one pair of Wyoming/California sites. The cross-correlation coefficient hovers around a value of 0.2 (low correlation, good diversity) for most of the year indicating a relatively high degree of diversity between the two sites. In the months where the correlation coefficient is higher, such as July, inspection shows that at least one of the sites (the Wyoming site in this case) has less energy available at that time. Thus, it is the use of the cross correlation coefficient and wind power density values together that indicates whether a particular pair of sites has both a good resource and good diversity or not. Site pairs that have high wind power densities and exhibit low correlation coefficients are excellent candidates for combining their resources.

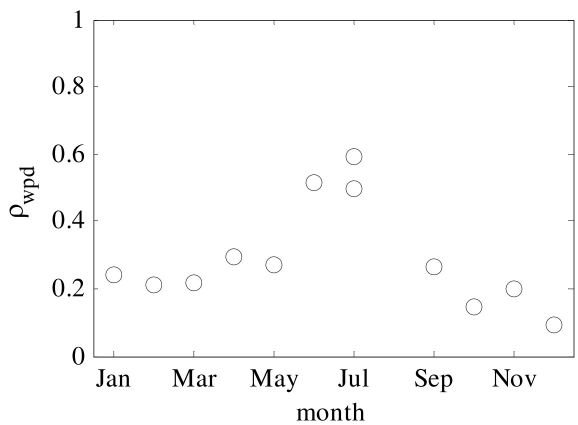


Figure 6 – Monthly cross correlation coefficient for wind power densities at Wheatland/Chugwater and Tehachapi Pass. Low values of the cross correlation coefficient represent better diversity.

Spatial Distribution of Correlation

Although the correlations between two points allow for the explanation of the diversity of two sites, they do not provide a larger view of diversity. To accomplish this, consideration of correlation maps is necessary. Figure 7 shows the correlation between Rawlins, WY and most of California, whereas Figure 8 shows the correlation between San Gorgonio Pass and Southeast Wyoming. In these correlation maps, low correlations (blues) represent sites that would provide diverse wind conditions for the location of interest. In contrast, higher values of the correlation (reds) indicate less diversity. Considering Figure 7, it is apparent that the winds in Rawlins, WY have a higher correlations (~0.5) only with the mountainous regions of California (particularly the Sierra-Nevada), and little correlation with the remainder of the State. In particular, the correlations between Rawlins and the indicated wind sites in California are quite low. Figure 8 indicates similar results between San Gorgonio Pass, CA and Southeast WY. There is a small region of higher correlation in the Laramie Valley (red coloring just above the SLV site), but this location has lower wind resources making the high correlation here less relevant. It is interesting that Wheatland/Chugwater has a correlation significantly lower than the other Wyoming sites demonstrating the diversity of the winds within Southeast Wyoming, although all the sites chosen have relatively low correlation with the winds at San Gorgonio Pass. Additional correlation maps for locations in California with Eastern Wyoming and for locations in Wyoming with California are provided in Appendix 1 – Wind Correlation Maps.

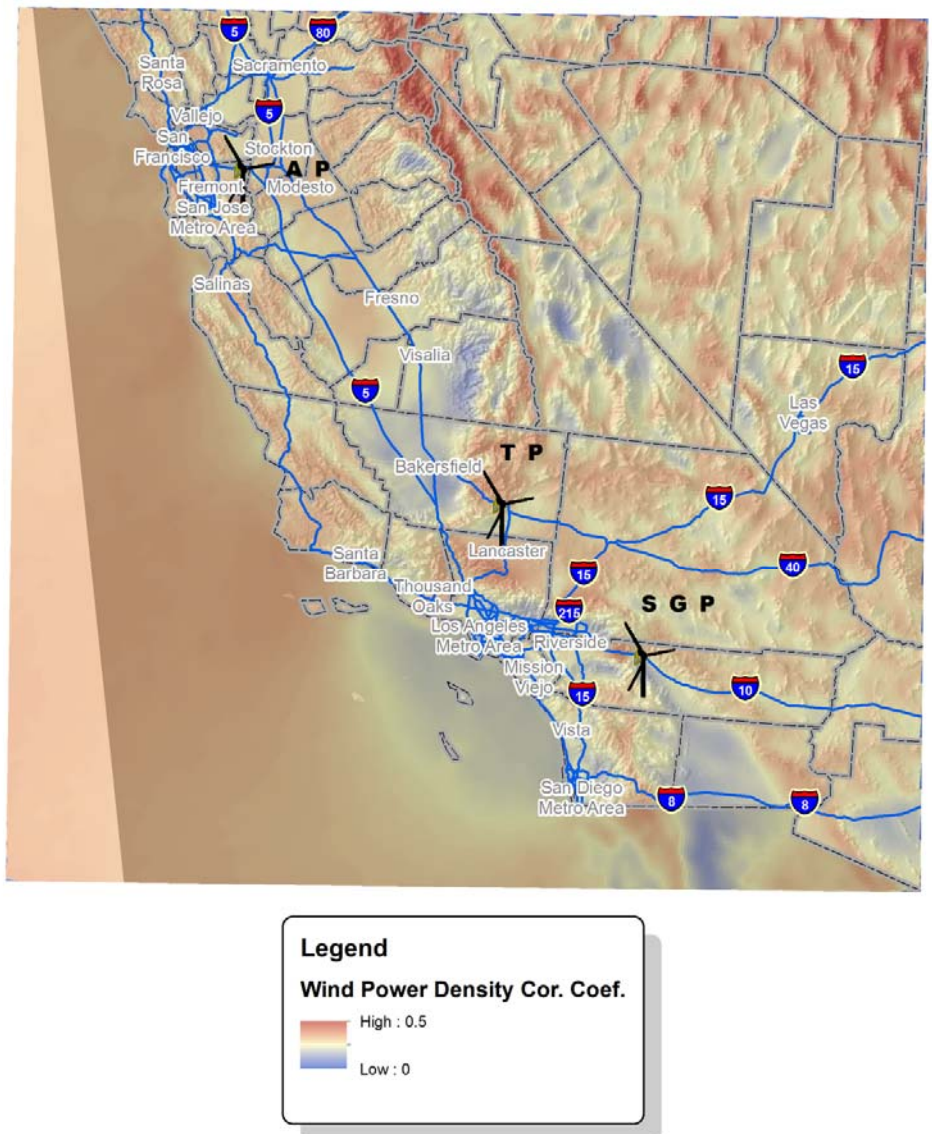


Figure 7 – Rawlins, WY / CA cross correlation map. Low values of the cross correlation coefficient between Rawlins and most sites in California indicate excellent wind diversity.

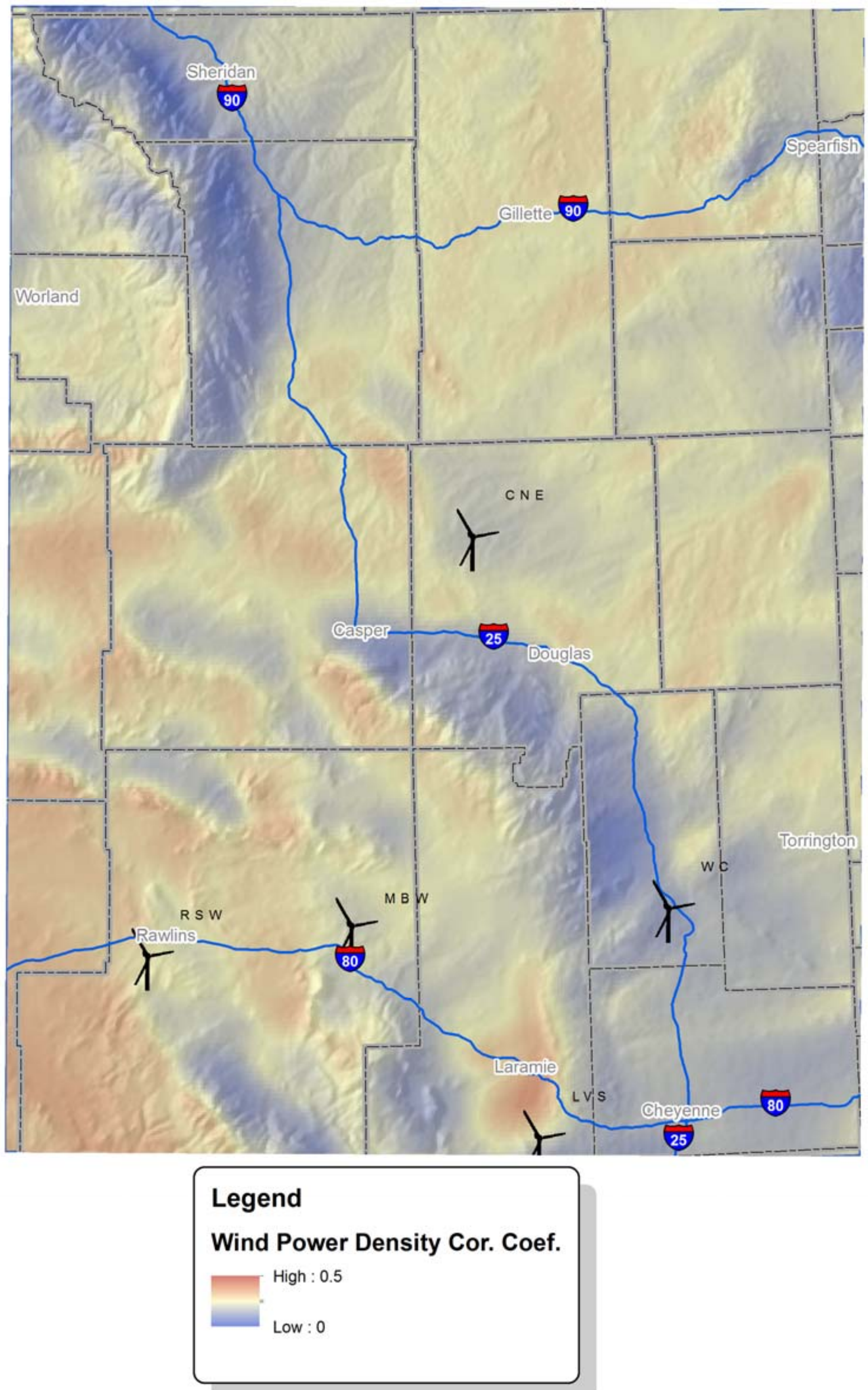
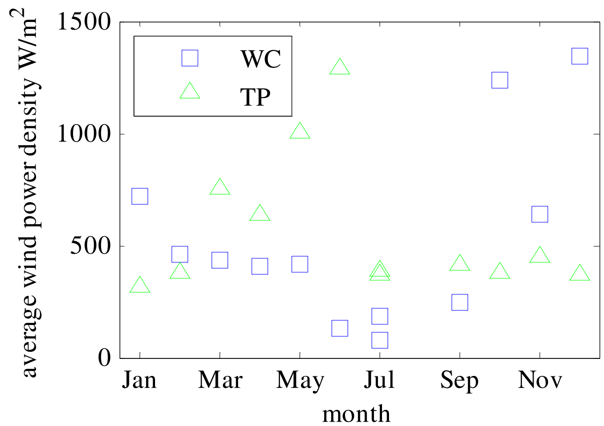


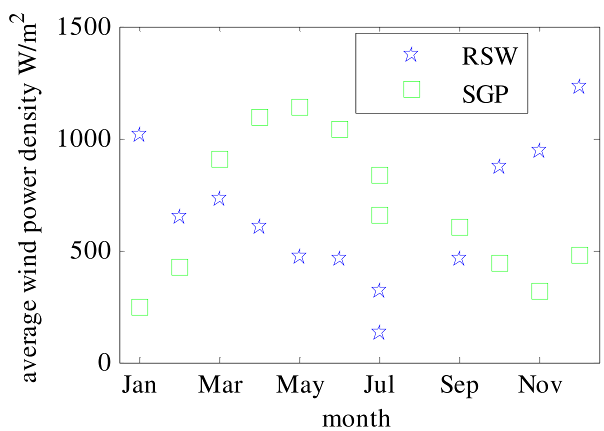
Figure 8 – San Gorgonio Pass, CA/ WY cross correlation map. Low values of the cross correlation coefficient between San Gorgonio Pass and most sites in Wyoming indicate excellent wind diversity.

Monthly Variations in Wind Speed

Although correlations are the best measure of overall diversity, other measures of diversity may also be useful. The monthly average wind power density focuses on seasonal variations of wind. As such, site-to-site comparison of these monthly averages provides a measure of seasonal effects on wind diversity. Diversity at two sites would be indicated by high wind power densities at one site while they are lower at the other and vice versa. Figure 9 shows the monthly average wind power density for two Wyoming-California wind site combinations. In both cases, the Wyoming sites show peak production in the late Fall and Winter, with lower production in the Summer. In contrast, the California sites wind resources peak in the Summer and then exhibit lower winds in the Winter. These trends are consistent with the sources of the winds in California and Wyoming.



(a)



(b)

Figure 9 – Monthly average wind power density comparisons: (a) Wheatland-Chugwater, WY (WC) and Tehachapi Pass, CA (TP), and (b) Rawlins, WY (RSW) and San Gorgonio Pass, CA (SGP). Pairs of locations that peak at different times of the year indicated seasonal diversity of the winds.

It should be noted that, although the monthly average wind power densities provide evidence of diversity, the correlations discussed above are better overall indicators of diversity. For specific uses, such as evaluating wind sites for meeting energy demand, plots such as those in Figure 9 may provide useful information.

Estimated Wind Power Production for Various Scenarios

Once candidate sites are selected from an analysis such as that above, the benefits of diversification can be investigated by considering the power output from different combinations of sites. In order to focus on diversity first, the individual sites were sized such that, in aggregate, they would equally contribute to a certain average power (1000 MW) based on their ideal capacity factor (the capacity factor determined from the modeled wind and turbine model – no accounting for down time, etc.). This also addresses any questions about the modeled data as the variability is the focus rather than the exact wind speeds.

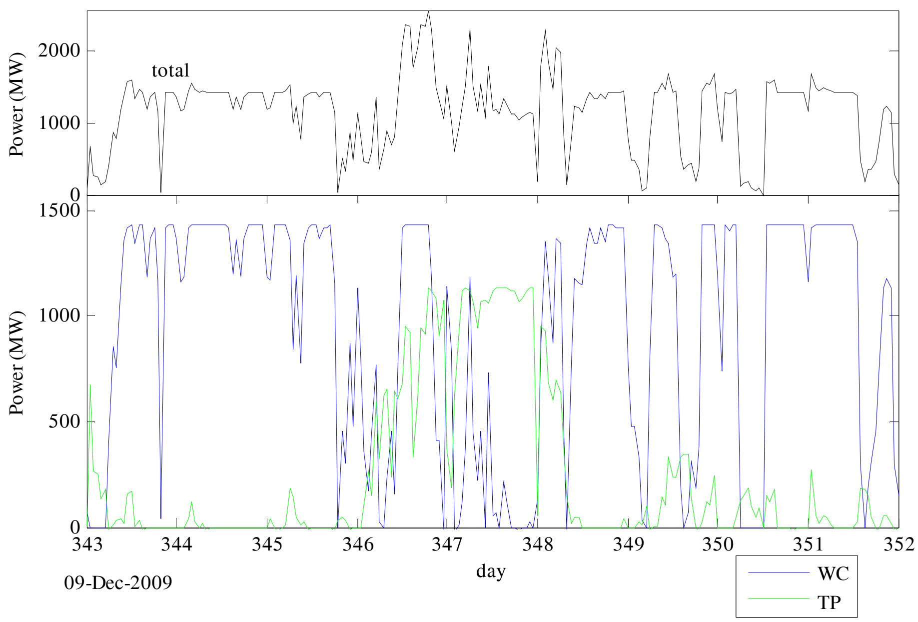


Figure 10 – Combined wind plant production for Wheatland/Chugwater, WY (WC) and Tehachapi, CA (TP) locations. The wind plant sizes were specified such that each individual farm contributes, on a yearly basis, half of the 1000 MW of average power.

The net effect of diversification is to smooth out the transients and to reduce the amount of time the combined production is at capacity or at zero output. This is clear in Figure 10 where two locations, Wheatland/Chugwater, WY and Tehachapi, CA, have been considered for producing an average of 1000 MW evenly divided between the two sites. Simulated power output over 10 days during December 2009 is shown in the figure. The individual outputs of the two locations indicate that this is a good time of year for production on Wyoming and less so for California. Rapid ramping events that are common at wind sites are observable at both locations, and several examples of ramping from zero output to near maximum production over periods as short as an hour (the temporal resolution of the simulations) are evident. The combined output tells quite a different story. Although the output is variable, the ramping events are much gentler and the power production only drops to zero once during the 10 day period. The one significant time that the Wyoming site experiences little wind coincides with a period of relatively high output from the California site. Addition of other sites produces even more consistent output. Such simulations are valuable for demonstrating the effects of diversity, but seasonal or yearly measures of the effectiveness of diversity are needed to allow for evaluation of a certain group of wind assets identified for diversity.

One means of categorizing the consistency of the output power is to consider the variability of the output over a certain period. To demonstrate this approach, several wind plants combinations were considered and the root mean square (standard deviation) of the power variations was calculated. So they can be fairly compared, the combinations of power production from individual sites were again specified such that each location contributed equally to the average power output of 1000 MW so a direct comparison of the variability is possible. Table 1 shows the results considering turbines located at two locations in both Wyoming and California. The combination of sites considered is indicated by the x's in the first four columns. Individual sites are first considered, and then multiple sites are combined to demonstrate the benefits of diversity. The important quantities in this table are the correlation coefficient and the rms power for each combination of plants, since a lower rms power is considered to be better since it represents lower variability. As shown in the table, the individual plants have rms power that is on the order of the average power generated. As additional assets are combined and the diversity increases (and the cross correlation decreases), the rms power drops in every case below that of the individual plants, with the exact rms power highly dependent on the individual sites combined. However, combining two locations with diverse wind resource drops the rms power into 60-70% of the mean power production. Increasing the number of contributing plants to four further decreases the rms power to ~55% of the mean power production. Although other measures of of variability may show other benefits, the rms power provides one means of assessing a particular wind diversity strategy.

Table 1 – Combined wind plant characteristics for different combinations of locations. In each case, the wind plants were specified such that each individual farm contributes its share of 1000 MW of average power. The lower the rms power, the better the combination as lower rms power represents lower variability. The numbers provided in the table are determined from the 1 year of simulation data.

San Gorgonio Pass	Tehachapi Pass	Wheatland/Chugwater	Rawlins	Average Power (MW)	rms Power (MW)	Wind Power Density Cross Correlation Coefficient
x				1000	1174	1.000
	x			1000	877	1.000
		x		1000	1089	1.000
			x	1000	833	1.000
x		x		1000	717	0.119
x			x	1000	677	0.262
	x	x		1000	635	0.171
	x		x	1000	601	0.344
x	x	x	x	1000	547	-

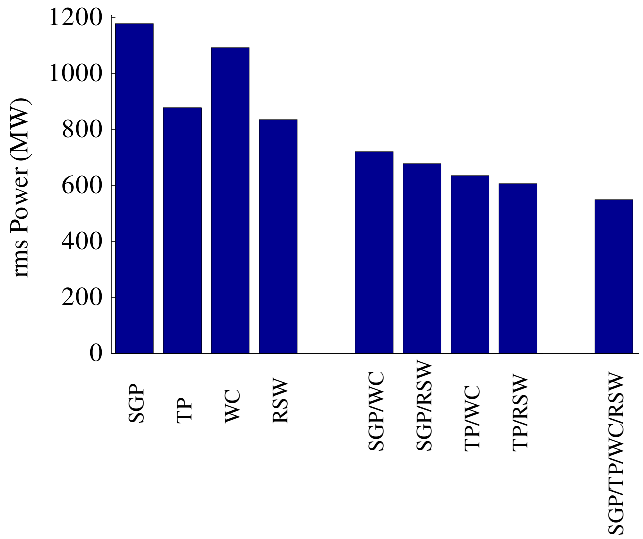


Figure 11 – Root mean square power variations for combined wind plant output: SGP – San Gorgonio Pass, CA, and TP – Tehachapi Pass, CA, WC – Wheatland /Chugwater, WY, RSW – Rawlins, WY. In each case, the wind plants were specified such that each individual farm contributes its share of 1000 MW of average power. The lower the rms power indicated by the bar, the better the site combination as lower rms power represents lower variability. The values in the plot are averages from the 1 year of simulation data.

To better visualize the diversity effect on variability, the rms power for each of the location combinations in Table 1 is shown in Figure 11. The individual farm variability is on the left of the figure, with variability for 2 and 4 plant combinations on the right. Recall that, the lower the rms power is, the better the performance of the combined wind plant output as lower rms power reflects lower variability. A steady decrease in the rms power is observed as the number of contributing plants increase. Note that the largest variability decrease is gained in moving from 1 site to 2 sites and the use of 4 sites has a reduced impact. This occurs because the four plants are still just from 2 regions, so the increase in diversity is limited. Combining a Wyoming/California pair with wind from another site (e.g. Eastern Colorado) would likely have a greater impact and should be further explored. A complete summary of the results from all tested Wyoming/California sites is provided in Appendix 2 – Wind Power Production Scenarios.

In the previous discussion, the average power output at different sites was assumed to be the same to focus on the variability effect and not the quality of the wind at the different sites. Here, the effect of the quality of the wind and the age of the wind installation on power production is considered by assigning capacity factors to the different sites. Consider three scenarios where 6000 MW of installed wind are distributed over different sites in Wyoming and California: 1) 3000 MW at San Gorgonio Pass and 3000 MW at Tehachapi Pass, 2) 3000 MW at Wheatland/Chugwater, 1500 MW at San Gorgonio Pass and 1500 MW at Tehachapi Pass, and 3) 3000 MW at Rawlins, 1500 MW at San Gorgonio Pass and 1500 MW at Tehachapi Pass. For this analysis, capacity factors of 30% were chosen for the California farms based on historical data, whereas capacity factors of 45%

were chosen for the Wyoming sites. Although the 30% capacity factor chosen for California is greater than those experienced today, it is considered to be a reasonable estimate of the capacity factor when older wind turbines are replaced with newer wind turbines in the future. The average (bars) and rms power (whiskers) output from these three different scenarios are shown in Figure 12. It is apparent that, as the Wyoming sites are added, the power indicated by the bars goes up (as would be expected for the higher capacity factors), but the rms power indicated by the whiskers actually goes down indicating that the variability is reduced. This demonstrates that high quality wind and geographic diversification both play a role in the nature of the power produced.

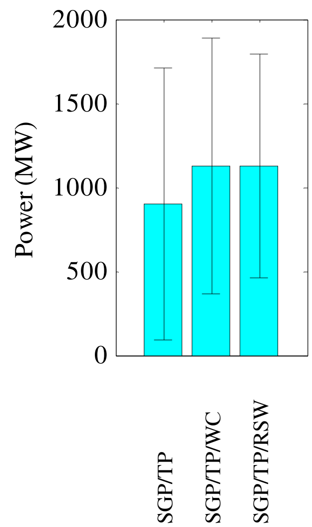


Figure 12 – Average power (bars) and root mean square power (whiskers) outputs from a combination of different wind sites in California and Wyoming: SGP – San Gorgonio Pass, CA, TP – Tehachapi Pass, CA, WC – Wheatland /Chugwater, WY, and RSW – Rawlins, WY. All three cases represent 6000MW of installed capacity. Higher power output and maintaining or decreasing rms power represent a beneficial outcome of combining electrical output from wind resources at different locations.

Although reducing variability is important, providing power when it is needed is also important. Consider Figure 13 where the hourly output (annual average) from two of the site combination scenarios is shown. Diversity in diurnal output is indicated by the power at the different plants peaking at different times. Such diversity is evident in Figure 13, which demonstrates that significant power is available throughout the time when California is likely to need the power – between 6 AM and 10 PM PST.

As example, consider the power produced by renewable sources on a specific summer day available to the California System Independent Operator (CAISO). Figure 14 shows the wind and solar output for this particular day, but also includes the output from potential Wyoming wind farms with 3000 MW of installed capacity. As expected from sites with good diversity, the Wyoming wind would continue to produce even as the wind assets in California are dropping. In fact, this example shows that the combination of Wyoming wind and California solar makes up for the drop in California wind during the day in this instance. Equally important is that production from Wyoming wind remains significant as the solar resource drops later in the day.

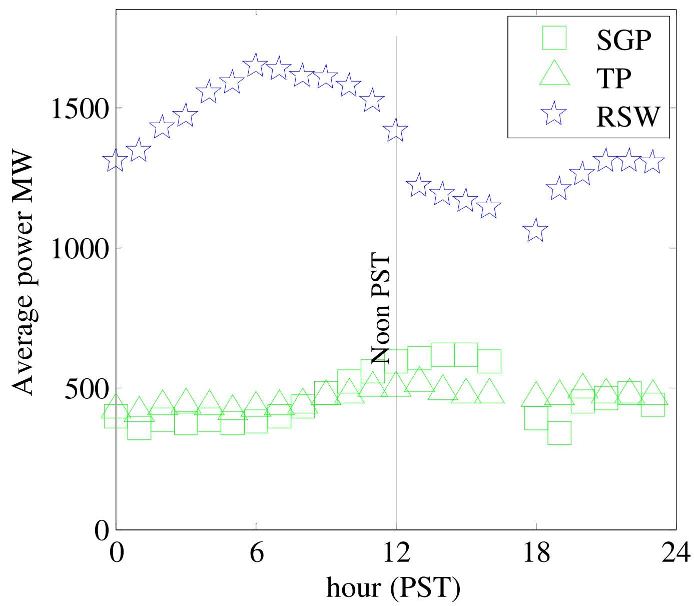


Figure 13 – Average diurnal variation of power production from three sites with different levels of installed capacity: 1500 MW at SGP, 1500 MW at TP, and 3000MW at RSW. Diversity is indicated in diurnal output when the period of maximum output power is shifted for the different sites.

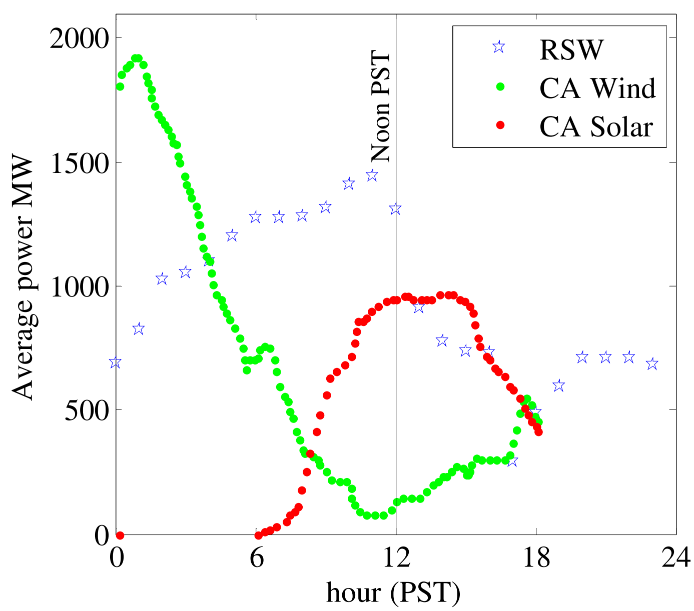


Figure 14- California wind and solar production on August 9, 2012 along with the summer diurnal output from 3000 MW of installed capacity in Rawlins, WY (RSW). The summer diurnal output for the Wyoming sites has been determined by averaging over the period June-September.

The previous figures demonstrated that the supply could be kept more constant using diverse resources, but how does the supply compare with demand? Figure 15 shows the relationship between the wind energy provided by a site in Wyoming combined with wind and solar from California (the sum of the resources shown in Figure 14) and the load on the CAISO system. The combined output is much more consistent, particularly during the middle of the day when power demand is growing, than when California wind and solar resources are considered alone.

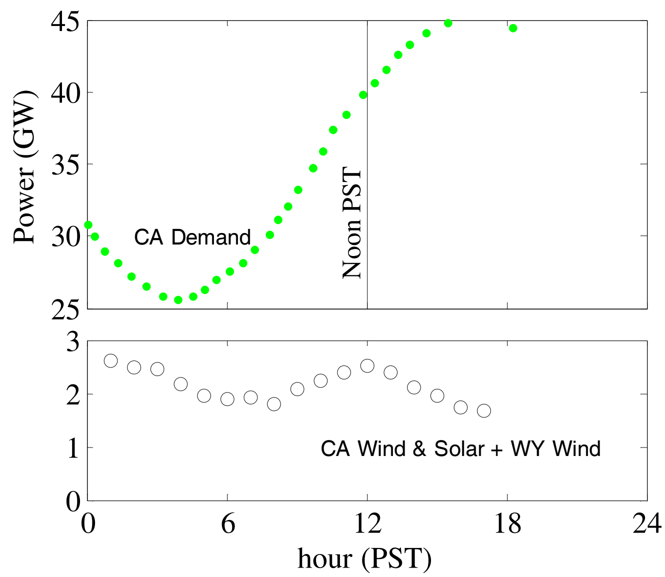


Figure 15 – Average summer output from a Wyoming site with 3000 MW capacity near Rawlins combined with actual California wind and solar production. Demand on the CAISO system is also shown. The California demand is for a single day August 9, 2012, whereas the wind power from Wyoming has been averaged over the June – September time frame.

Consider a similar example, but now during the winter. At this time, California solar and wind produce less output on average than in the summer and Wyoming's wind is normally at its highest output. As shown in Figure 16, power from Wyoming wind is typically consistent throughout the day during the winter. This is particularly important later in the day as the drop in California solar corresponds to an increase in the load as shown in Figure 17. This result also emphasizes that diversity of renewable power resources will become even more important as the penetration of renewable (e.g. California solar production) grows.

Although these summer and winter cases shown in Figure 14-Figure 17 are only examples and the situation may differ on any particular day, the previous diversity suggests that, on average, Wyoming's wind would be complementary to California's own renewable resources and such examples would be typical.

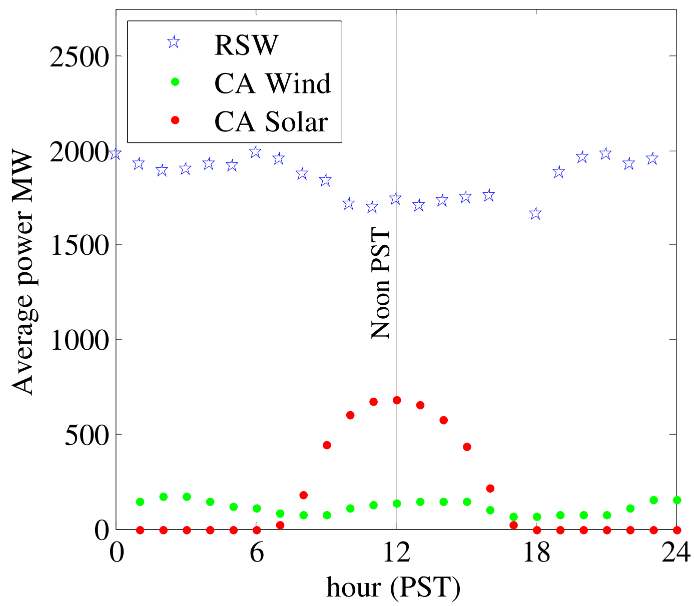


Figure 16- Average California wind and solar production for November 12-16, 2012 along with the winter diurnal output from 3000 MW of installed capacity in Rawlins, WY (RSW). The winter diurnal output for the Wyoming sites has been determined by averaging over the November-January period.

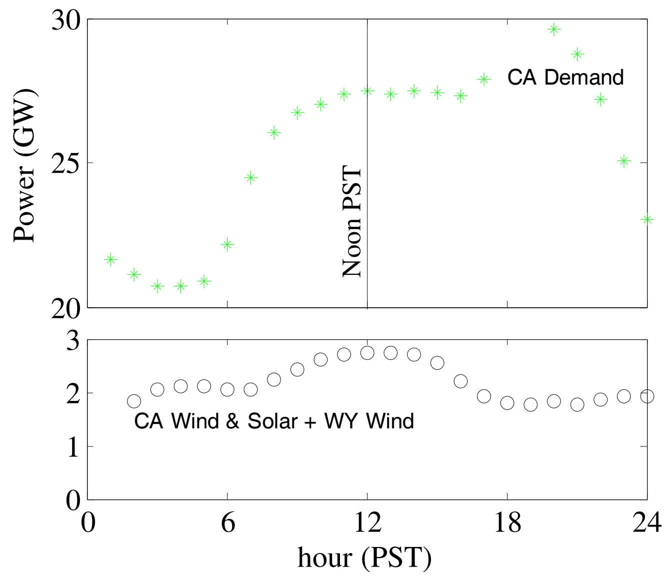


Figure 17 – Average winter output from a Wyoming site with 3000 MW capacity near Rawlins combined with actual California wind and solar production. Demand on the CAISO system is also shown. The California demand is a five day average for November 12-16, 2012, whereas the wind power from Wyoming has been averaged over the November – January time frame.

Evaluation of Cost Savings

Although the effects of diversification on amount and variability of power produced have been considered, the impact of these effects on cost has not been discussed. To address this issue, aggregate output from different wind plants specified by the three scenarios given above have been determined for one year. A 10-day record of the aggregate output is shown in Figure 18 for each of the three scenarios. The solid black line in the figure represents 25% of the total installed capacity. When power drops below a certain level during heavy use periods of the day, it would be necessary to purchase makeup power from other electricity generating sources. It is clear to see that scenario 1 spends more time below the 25% capacity line than scenarios 2 and 3, implying that more power would need to be purchased in this case.

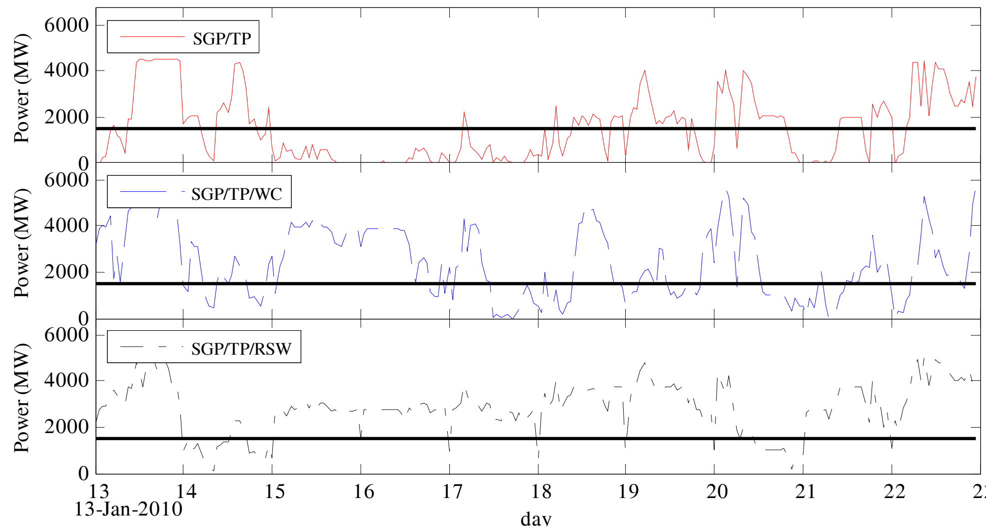


Figure 18 – Hourly aggregate output from combinations of wind farms for the three scenarios discussed above over a 10 day period. The dark line shown in each plot represents 25% of the total installed capacity.

To determine a cost associated with purchased makeup power, a simple approach was taken. It was assumed that power is purchased when production drops below 25% of the installed capacity (production below 1500 MW associated with the black solid line in Figure 18) between the hours of 6 AM and 10 PM PST, from which an annual cost of purchased power can be determined. Figure 19 shows the cost of makeup power for the same three scenarios previously discussed for different power purchase prices. The combination of two California sites is given by the red curve, whereas the other two curves have a Wyoming site partnered with the same two California sites. Although the analysis needed to estimate actual cost savings is likely to be more complex, it is clear that the difference in make-up power costs between the all California and mixed California-Wyoming scenarios is in the 10's to 100's of millions of dollars annually. Considering that the wind-derived power delivered to California from Wyoming could reach four times the amount assumed here, the economic benefits of geographic diversification are clear.

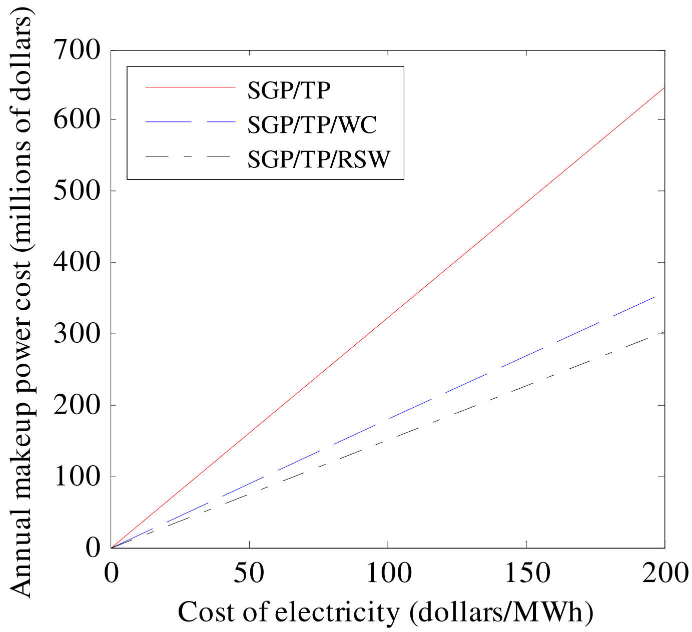


Figure 19 – Annual cost to purchase makeup power for different wind sites in California and Wyoming All three cases represent 6000MW of installed capacity, and power is purchased whenever the aggregate output of the three plants drops below 1500 MW or 25% of the installed capacity. Note that the projected savings apply only to the time period between 6:00 AM and 10:00 PM daily.

Conclusions & Future Work

A consideration of the diversity of existing and future wind energy production sites in Wyoming and California has been carried out using wind data extracted from weather forecasting simulations. Although the simulated wind resource may not be an exact representation of the resources at a given site, and the results should be considered with this in mind, the trends determined from using them in this analysis should be indicative of what would be experienced for a given wind diversification strategy. The simulations show that statistics (particularly the cross correlation of the wind power density at two locations) may be used to identify good wind diversity partners. Subsequent wind power estimates provide metrics upon which the wind diversity can be evaluated. In all cases studied here, the diversity decreased the variability of the power production, with large reductions (order of 1/3 to 1/2) experienced when up to four wind assets were combined. Such results indicate that diversification of wind assets is an additional tool to power backing and eventually grid storage in addressing the variability of both power supply and demand. A simple analysis considering the cost of buying power when the wind assets fail to produce a sufficient amount of power indicated annual savings in the \$10s-\$100s of millions of dollars are possible through geographic diversification. For example, Figure 19 indicates that the reduction in makeup power through the combination of Wyoming and California sites (as opposed to California sites only) is estimated to yield annual savings of $100 million when makeup power is priced at $50/MWh.

The results of this analysis have several important implications. Decrease in variability and increase in correlation with demand that can occur when diverse renewable resources are used should make it easier to integrate these resources within the limitations of the existing grid. In addition, the reduction of ramping events will not only reduce the costs associated with purchasing backup power, but has the potential to reduce greenhouse gas emissions assuming the backup power is provided by fossil fuels. Finally, diversification has the potential to allow California to develop its own indigenous renewable resources further as the variability and ramping issues that are present today will only grow greater as the amount of power supplied by California renewable resources increases.

Next Steps

Although these results are promising, further work should be performed. Field measurements of the wind resource or wind energy production should be used as available to verify the results presented here. In addition, multiple years of wind simulation data should be used to determine the cross correlations in order to obtain statistics that are more typical of an average year. Correlation with multiple years of CAISO data would also better capture the typical effects of diversity on meeting load demands. Nonetheless, this work shows the power of such analysis and the assistance it can provide to developers when determining where to build wind farms. In addition to the price of renewable energy, diversity analysis would be valuable for utilities and operators to determine from where they should obtain their wind energy power and the additional monetary savings to expect from their efforts to diversify their wind power purchases.

References

[1] ***Wind Powering America, Wyoming Wind Map and Wind Resource Potential, http://www.windpoweringamerica.gov/wind_resource_maps.asp?stateab=wy .***

[2] ***Database of State Incentives for Renewables and Efficiency (DSIRE), http://www.dsireusa.org/.***

[3] ***Western Electric Coordinating Council, "10-Year Regional Transmission Plan, 2019 Study Report," September 2011.***

[4] ***J. Naughton, J. Baker, and T. Parish, "Wind Diversity in Wyoming," Wind Energy Research Center Report, to be published in 2013.***

[5] ***D. Yen-Nakafuji, "California Wind Resources," California Energy Commission Report CEC-500-2005-071-D. April 2005.***

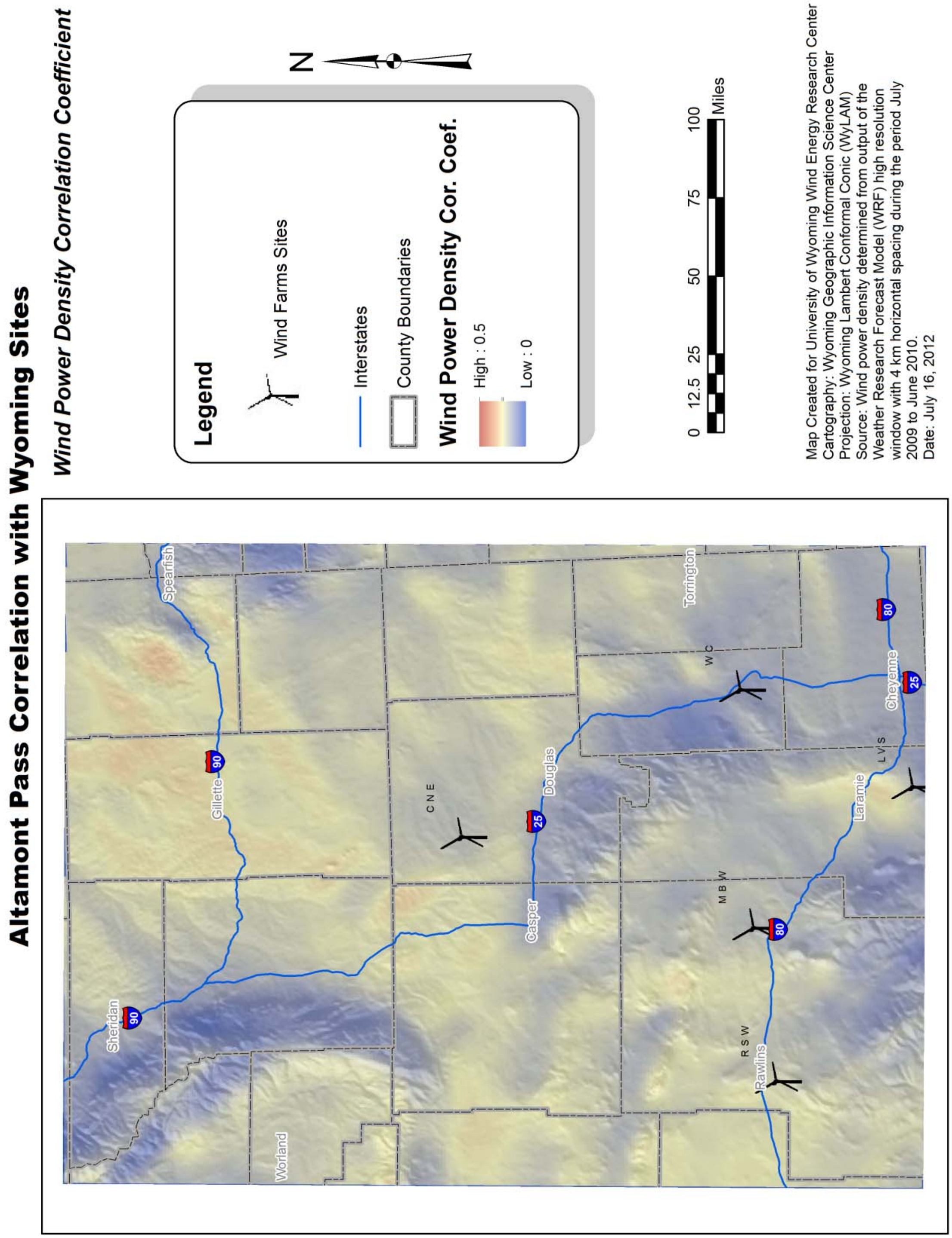
[6] ***"Renewable Energy Cost of Generation Update," CEC-500-2009-064, August 2009, pp.105-106.***

[7] ***J.S. Bendat and A.G. Piersol, Random Data Analysis, 2nd Edition, John Wiley and Sons, New York, pp.109-113.***

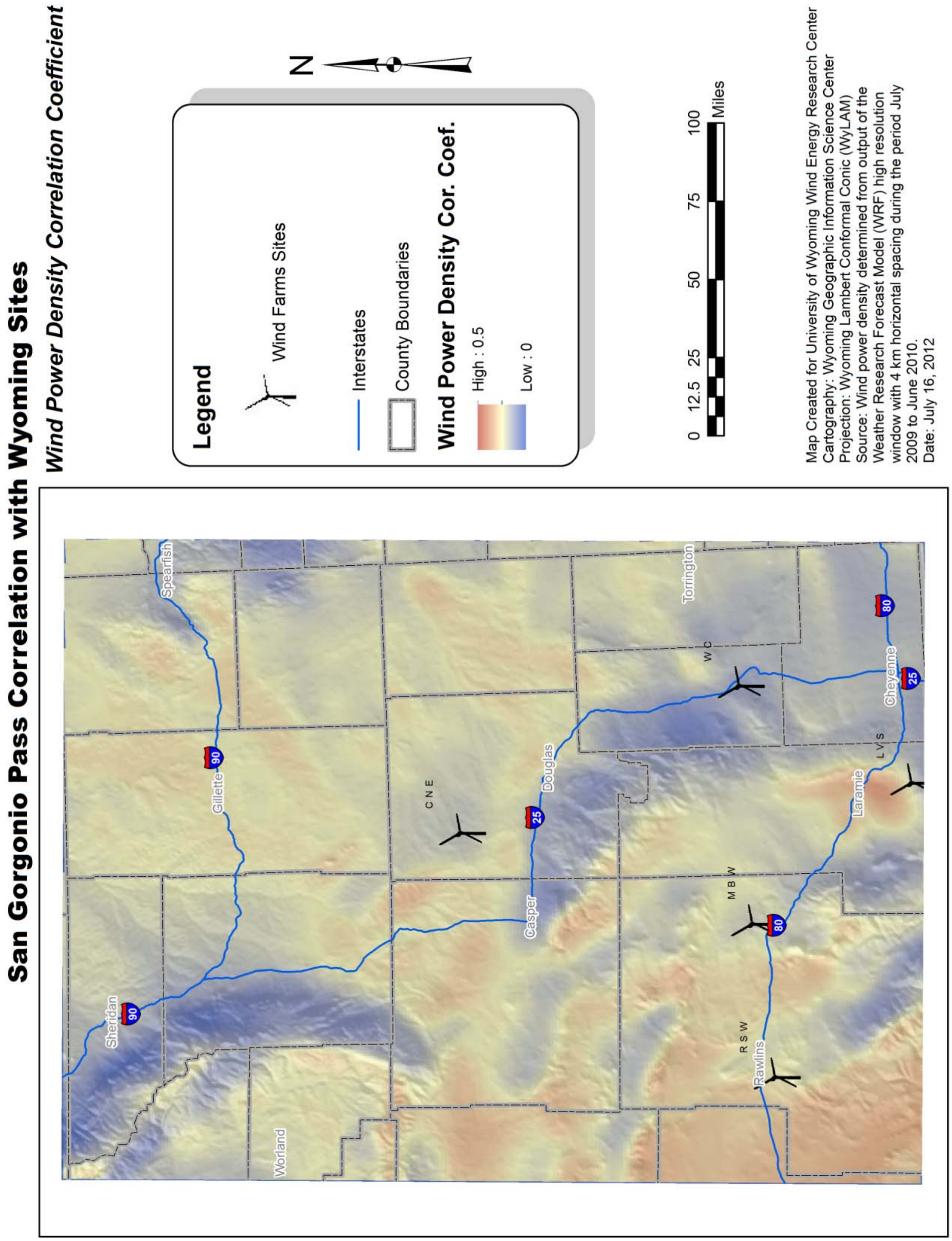
Appendix 1 – Wind Correlation Maps

A limited number of wind correlations maps were provided in the main text. Below, a complete set of correlation maps corresponding to each of the Wyoming and California wind sites chosen is provided. To facilitate their use, each is provided as a standalone graphic.

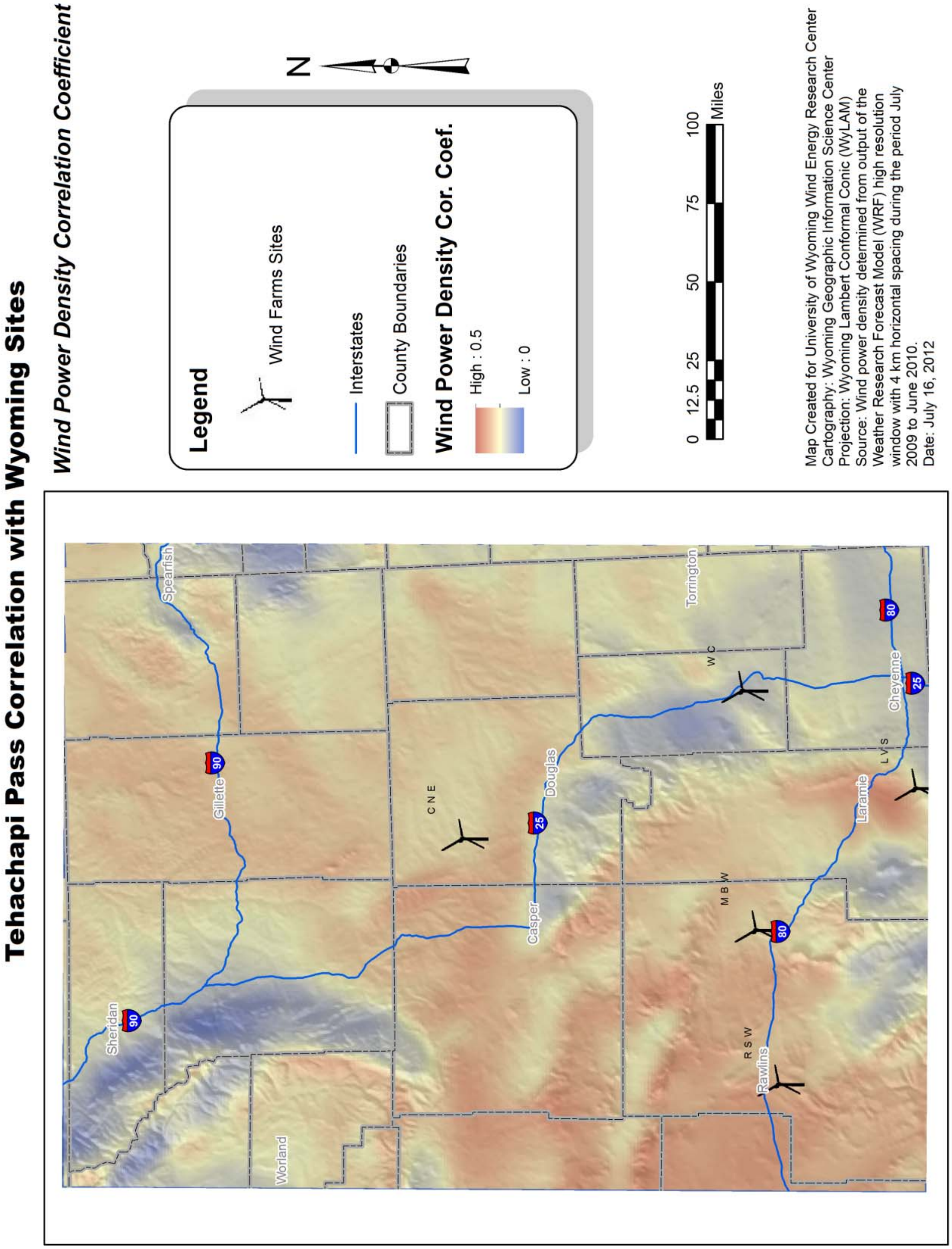
Altamont Pass, CA



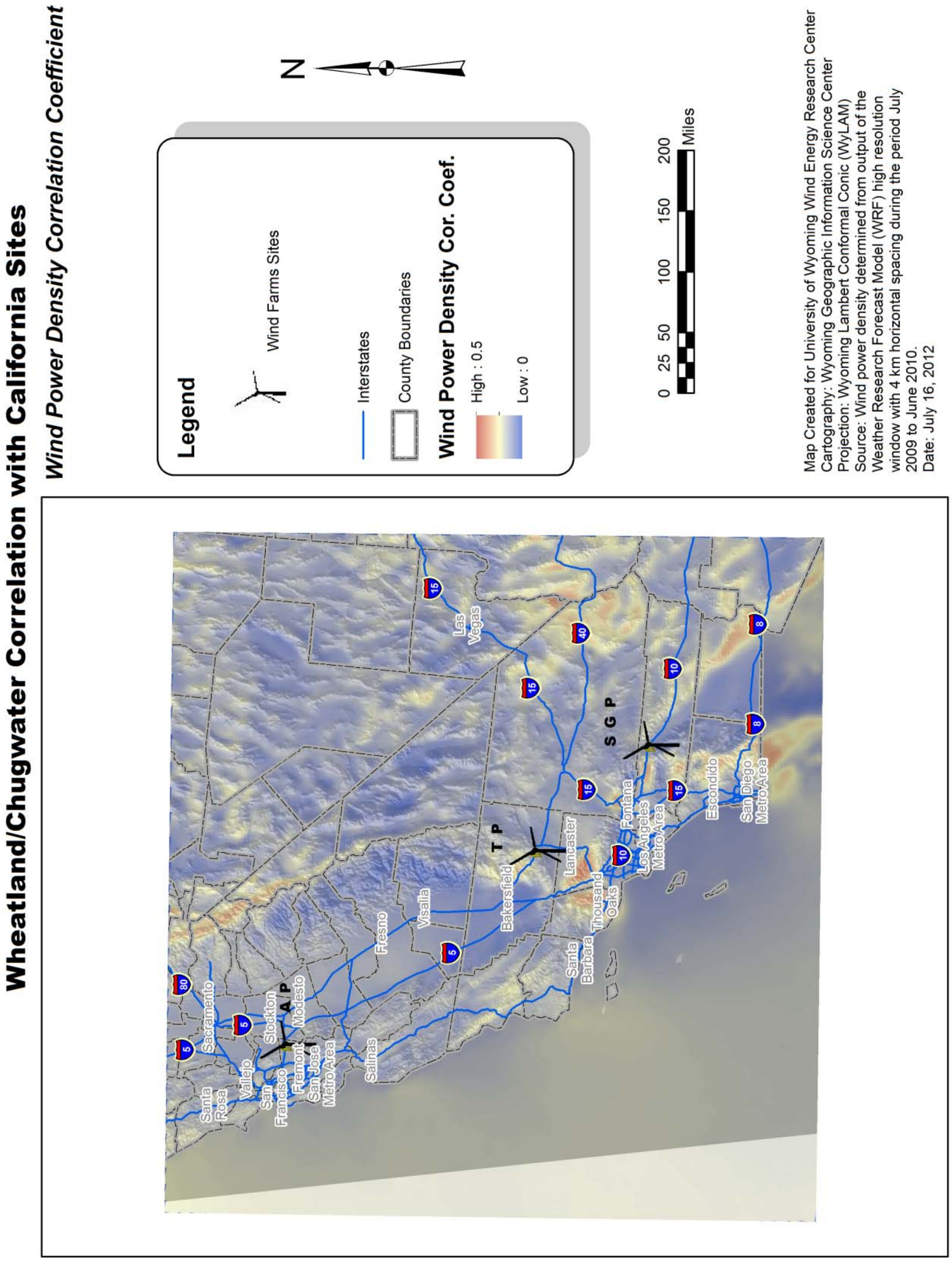
San Gorgonio Pass, CA



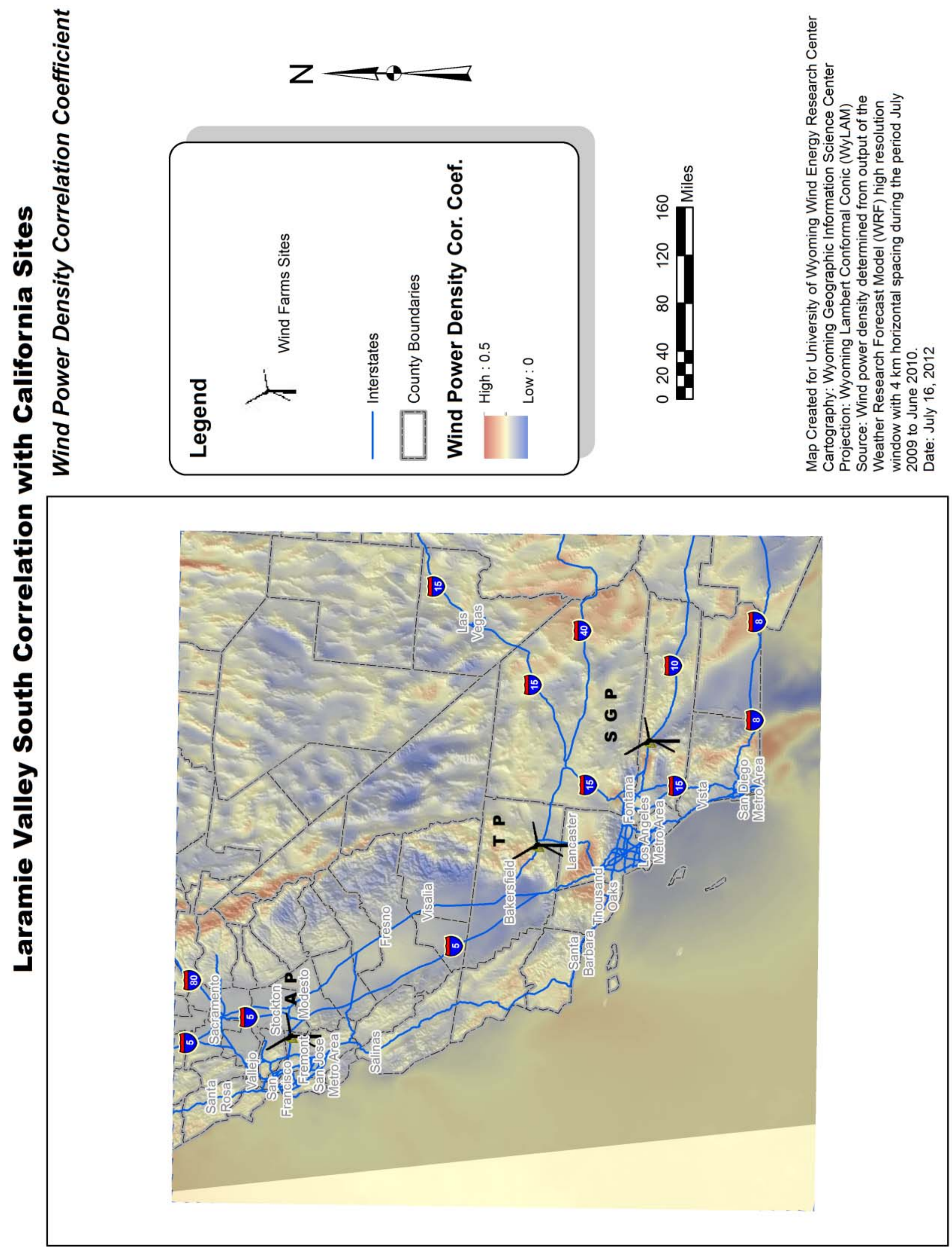
Tehachapi, CA



Wheatland/Chugwater, WY



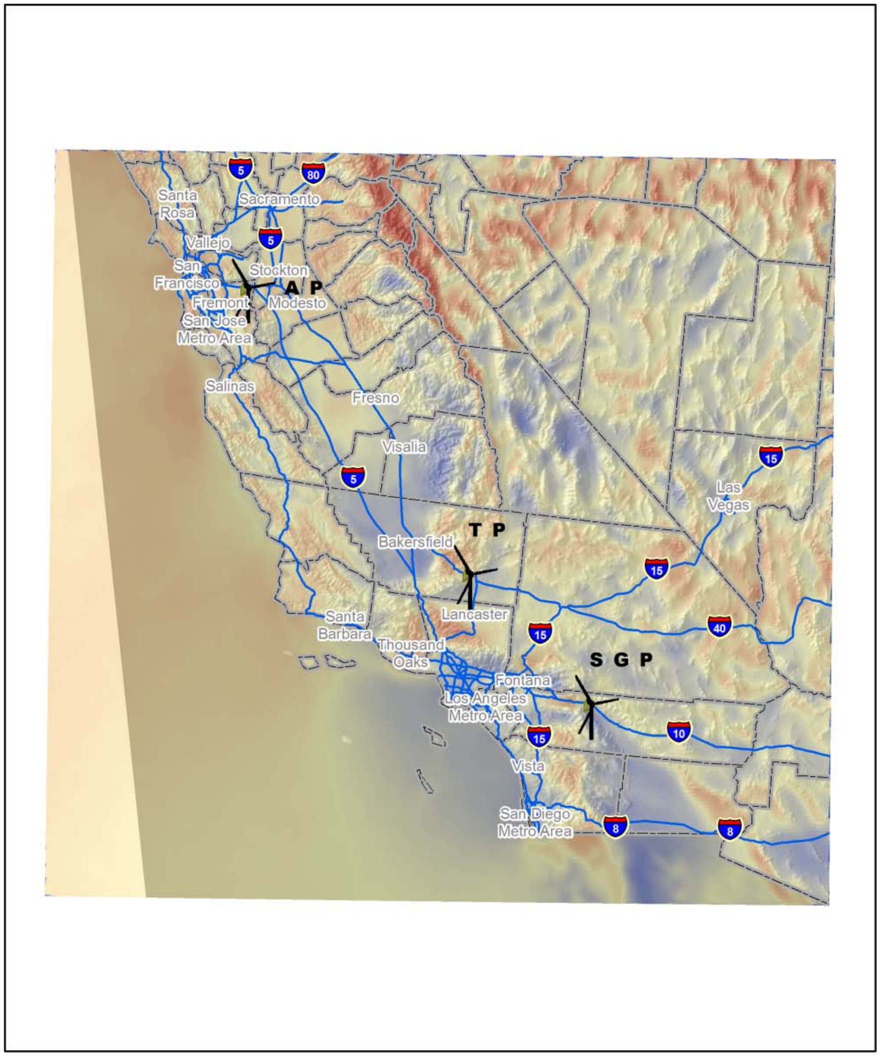
Laramie Valley, WY



Casper, WY

Casper Northeast Correlation with California Sites

Wind Power Density Correlation Coefficient



Legend

Wind Farms Sites

Interstates

County Boundaries

Wind Power Density Cor. Coef.

High : 0.5

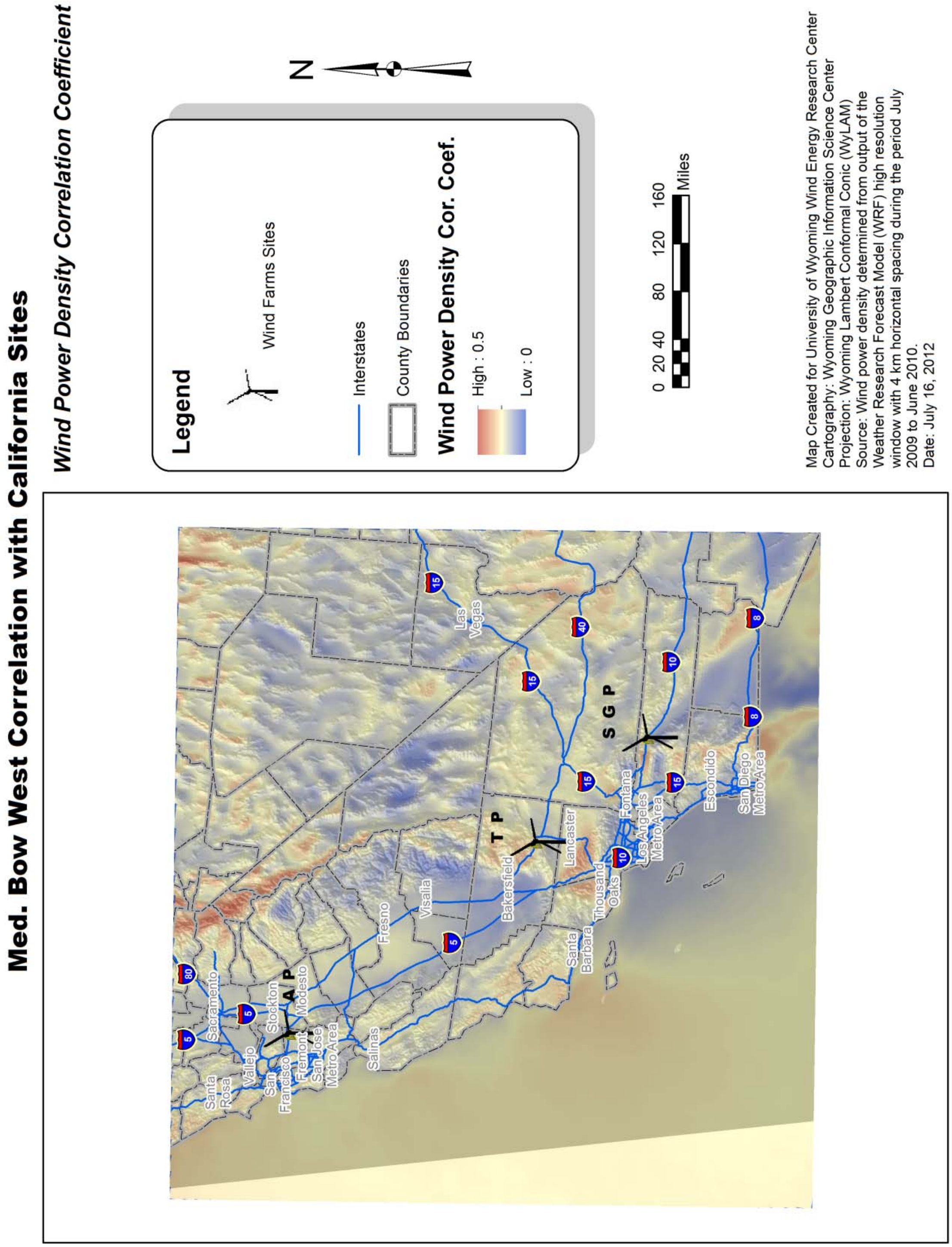
Low : 0

N

0 25 50 100 150 200 Miles

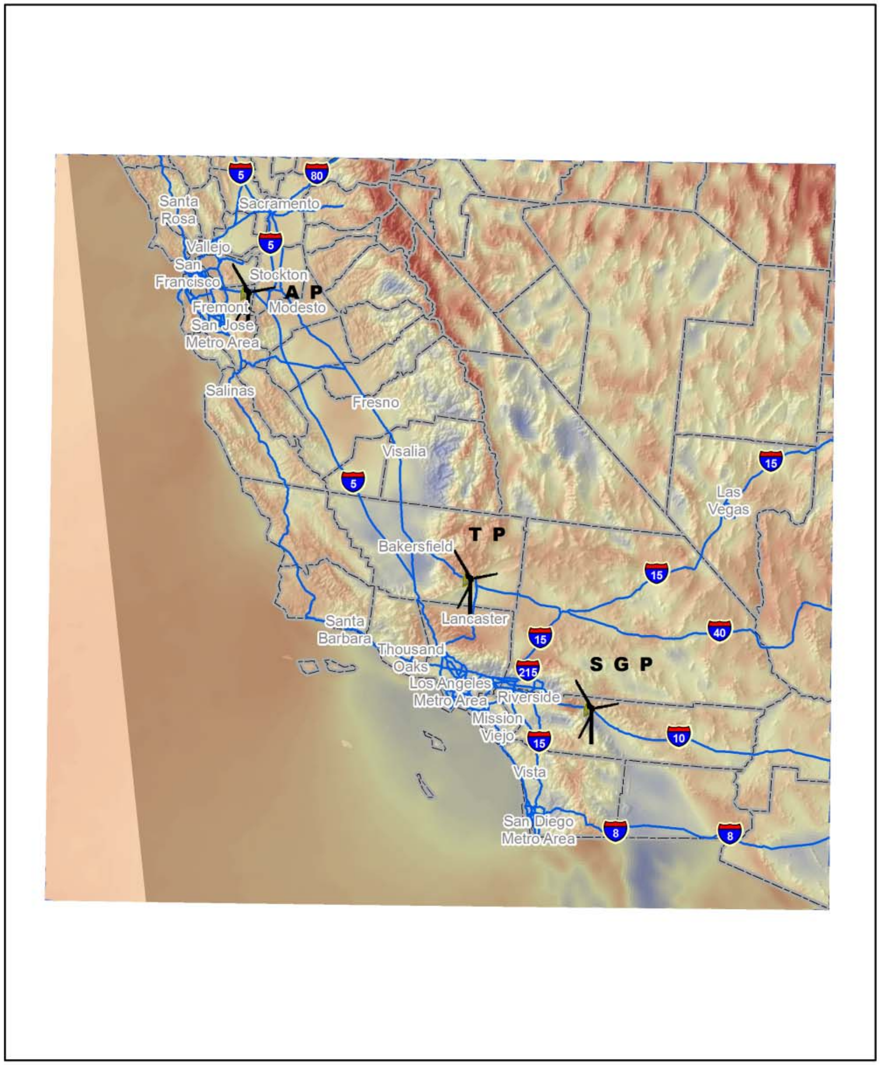
Map Created for University of Wyoming Wind Energy Research Center
Cartography: Wyoming Geographic Information Science Center
Projection: Wyoming Lambert Conformal Conic (WyLAM)
Source: Wind power density determined from output of the Weather Research Forecast Model (WRF) high resolution window with 4 km horizontal spacing during the period July 2009 to June 2010.
Date: July 16, 2012

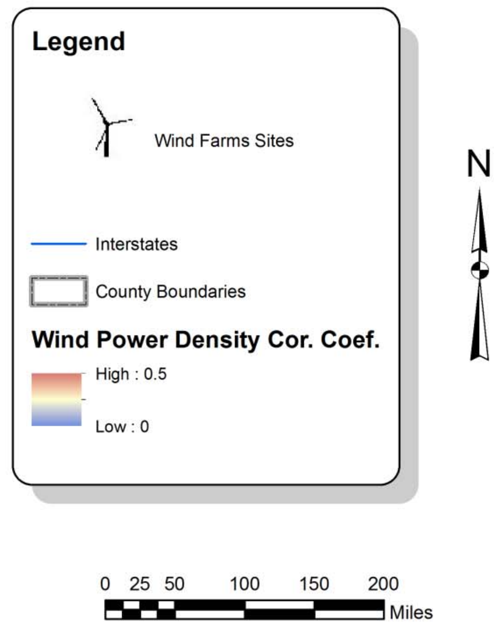
Medicine Bow, WY



Rawlins Southwest Correlation with California Sites

Wind Power Density Correlation Coefficient





Map Created for University of Wyoming Wind Energy Research Center
Cartography: Wyoming Geographic Information Science Center
Projection: Wyoming Lambert Conformal Conic (WyLAM)
Source: Wind power density determined from output of the Weather Research Forecast Model (WRF) high resolution window with 4 km horizontal spacing during the period July 2009 to June 2010.
Date: July 16, 2012

Appendix 2 – Wind Power Production Scenarios

Only a subset of Wyoming/California wind site combinations were presented in the main body of the report. Here the average and rms power as well as the cross correlation of the wind power density for all locations tested are tabulated. A total of 1000 MW of installed capacity for each combination was assumed. The trends that were observed in the main text hold here. All the two-site combinations exhibit significantly reduced variability in the output power compared to either installation alone.

Table A2-1 - Power production for various assumed combinations of California and Wyoming wind locations.

Altamont Pass	San Gorgonio Pass	Tehachapi Pass	Wheatland/Chugwater	Laramie Valley	Casper	Medicine Bow	Rawlins	Average Power (MW)	rms Power (MW)	Wind Power Density Cross Correlation Coefficient
x								1000	1340.7	1.000
	x							1000	1174.4	1.000
		x						1000	877.0	1.000
			x					1000	1089.2	1.000
				x				1000	844.6	1.000
					x			1000	934.7	1.000
						x		1000	872.1	1.000
							x	1000	833.4	1.000
x			x					1000	748.0	0.120
x				x				1000	702.2	0.170
x					x			1000	704.9	0.184
x						x		1000	700.3	0.175
x							x	1000	698.2	0.222
	x		x					1000	716.6	0.119
	x			x				1000	680.5	0.215
	x				x			1000	684.3	0.189
	x					x		1000	674.0	0.202
	x						x	1000	676.7	0.262
		x	x					1000	634.9	0.171
		x		x				1000	592.9	0.268
		x			x			1000	608.4	0.270
		x				x		1000	601.7	0.275
		x					x	1000	600.6	0.344