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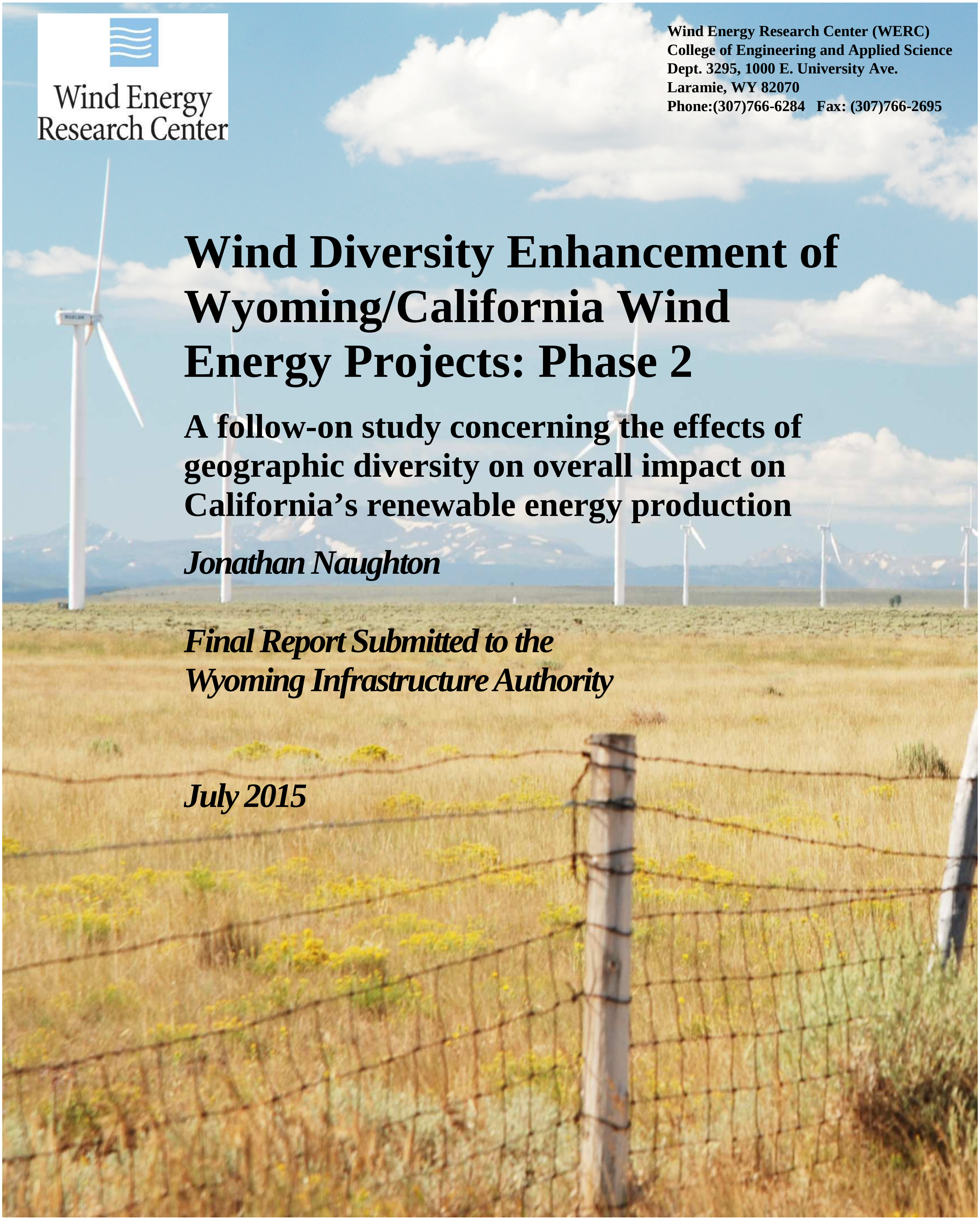

Wind Diversity Enhancement of Wyoming/California Wind Energy Projects: Phase 2

A follow-on study concerning the effects of geographic diversity on overall impact on California's renewable energy production

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This report is a follow on to an earlier study entitled "Wind Diversity Enhancement of Wyoming/California Wind Energy Projects."

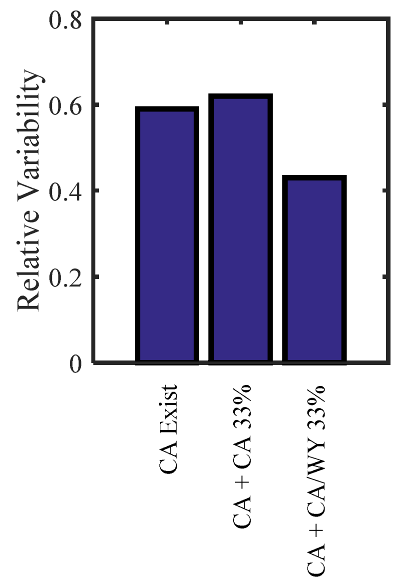
Executive Summary

On January 25, 2013, the Wyoming Infrastructure Authority (WIA) released the University of Wyoming's "Wind Diversity Enhancement of Wyoming/California Wind Energy Projects." The 2013 Study was based on one (1) year of modeled data.

This study, also commissioned by the WIA, addresses the impact of diversifying the mix of renewable energy assets used in California's electrical system. The study was carried out using 10-minute wind data from meteorological towers in Wyoming combined with actual 10-minute average wind and solar electrical production data from California to perform this assessment. The results of this report confirmed the findings of the earlier report, but goes on to provide an objective means of evaluating different combinations of renewable assets. Concrete examples of the benefits of diversity are then provided. The highlights of the results are the following.

- Due to the geographical difference in renewable energy resource availability, high Wyoming wind energy production often occurs during periods when California renewable energy production is low. Results using field data from Wyoming and production data from California support the results of an earlier report that only used modeled data (Wind Diversity Enhancement of Wyoming/California Wind Energy Projects). Correlation, the parameter used to quantify diversity, was found to behave in the same way as the modeled data suggested. In addition, seasonal and diurnal characteristics of wind in Wyoming and that in California were shown to be complementary as diversity would suggest.
- A group of Renewable Energy Quality Metrics (REQMs) is developed and applied to several different renewable energy scenarios. The metrics provide an objective means for characterizing the behavior of different combinations of renewable energy assets when added to existing assets so that the resulting resource mixes can be compared. The analysis can be applied to small scale (e.g. utility), regional scale (e.g. system operators), and national scale (e.g. western interconnect) perspectives.
- When applied to California's electrical system, these metrics indicate that, relative to the existing renewable energy sources in California, adding Wyoming generated electricity to California's existing renewable assets increases the performance metrics in all categories. Adding high capacity factor Wyoming wind results in better metrics then adding more California renewables.
    - One of these metrics (the relative variability) indicates the amount of variation in the power availability from a group of renewables, so lower numbers are better. As evident in the bar graph, this study shows that the relative variability worsens (it increases) when additional California renewables (CA + CA 33%) are added to the existing California renewables (CA Exist), and improves (it drops) when Wyoming wind is added (CA + WY 33%).

- These Renewable Energy Quality Metrics (REQMs) provide an additional tool that can be used by decision makers (utilities, system operators, and policy makers) to help in choosing which renewables to add to their systems by providing an objective means of comparing different options.
    - A companion white paper on these quality metrics authored by James Detmers will be released shortly highlighting the application of these metrics for real electrical systems.



Relative variability for three of the scenarios investigated in this study.

- Example benefits of diversifying renewable energy assets are provided in terms of quantities important to electricity generation, storage, and distribution, as well as in terms of environmental impacts. Combining diverse renewable assets can produce the following results.
    - A decrease in water use as well a reduction of greenhouse gas emissions are observed. Comparing the addition of 6000 MW of California renewables to 6000 MW split between California renewables and Wyoming wind yielded water savings in the billion gallon range and CO_2 reductions in the millions of tons.
    - A cost savings resulting from reduced backup generation is observed. For a 6000 MW addition, a combined Wyoming/California solutions yielded saving of 100s of millions in dollars annually when compared to an all California solution.
    - A reduction in flexible capacity ramping requirements that cause large price increases.
    - A reduction in the amount of storage needed to support renewables at a given level is indicated. When comparing a Wyoming/California mix of renewable energy added to the existing California renewables, a simplified analysis suggested a significant reduction in the amount of storage per GW-hr of energy generated necessary to meet a given demand without additional stand-by support from non-renewable generation sources.

Note that some of these benefits listed above are a mix of increased capacity factors as well as geographical diversity as the two effects are often hard to separate. However, these impacts are important to consider as California continues to build out its renewable portfolio. In particular, the results of the storage analysis suggest that geographical diversification can help reduce the amount of storage needed to support variable resources.

This study clearly demonstrates the benefits of diversity, and it is hoped that it spurs additional work by others including utilities and system operators to further analyze and quantify these benefits for specific cases. With the recent push to increase California's renewable energy portfolio from 33% to 50%, considering new renewable resources that provide geographical diversity, and, as has been shown here, Wyoming's high capacity factor wind in particular, would be in California's best interest. With additional coal-fired plants shutting down over the next several years and additional closures of power plants due to the phase-out of once-through cooling, the opportunities for renewable energy to expand its footprint will be available.

The results of this study were initially presented at the Wyoming Infrastructure Authority's Spring Energy Conference on June 11-12, 2015 at the Little America Resort in Cheyenne, WY. The Conference Agenda is posted on the WIA's website.[1]

Complementary to the analysis performed herein is a companion work being performed by Mr. James Detmers, former COO, CAISO. Mr. Detmers' work "New Metrics for Acquiring Renewable Energy." A paper on this work is being released at the same time as this report, and preliminary results were presented at the WIA's 2015 Spring Energy Conference.

[1] http://wyia.org/events/board-meetings/

Introduction

The increased penetration of wind-generated power into the electrical grid over the past decade has been impressive. Between 2003 and 2013, the amount of energy generated by wind increased by a factor of 15 from approximately 0.3% of U.S. electrical consumption to 4.3% [1]. Recent EPA rules are likely to cause the shut-down of a significant percentage of existing coal-fired generation, a portion of which is likely to be replaced by renewables. The need for such replacement generation coupled with renewable energy portfolios in states like California, where portfolios requiring up to 50% are being considered, are likely to continue the demand for renewables for years to come. As positive as the future may appear for renewables, the ability to integrate electricity generated from such sources becomes more challenging with respect to grid stability and reliability as the percentage increases due to the variability of electricity production associated with renewables. When renewable energy was a very small component of the electricity generation infrastructure, the details of its production schedule were not all that important. With today's increased generation, those details of the generation schedule become more important as the rapid increase of solar power in California has demonstrated.

Addressing the variability issue is difficult whether using traditional approaches or those that are yet to be developed. Rapid start gas turbines can be used to provide makeup power when renewable resources drop off, but relying on this approach too heavily becomes expensive due to the capital expenditures required for an asset that is used a limited amount of time. Energy storage is another solution that has been considered [2], but it is an area where grid-size storage is still limited. As storage technology evolves, it will certainly become a part of the solution to variability, but it is likely to remain expensive due to the technology required and the losses incurred in first storing the power and then later retrieving it. Thus, limiting the amount of storage required is beneficial to keeping the cost of electricity down.

Another possible means of addressing this variability issue that has received some attention is resource diversity, or using variable resources from different locations. Despite the discussion, there are few places where diversification as related to grid operation and related economic impact has been considered in detail. In the first phase of the current effort [3], the case for diversification of wind resources was presented. Using modeled data, the report showed how to identify diverse wind resources, and then went on to demonstrate some of the potential benefits of using diverse resources rather than just using those resources found locally.

Since that report, other studies have considered the benefits of geographic and resource diversity. As penetration of renewable energy increases, a prime concern is over-generation, which a report by E3 in January 2014 found was a particular concern at high solar penetration [2]. Over-generation tends to scale with the amount of capacity and, without other mitigation strategies, results in curtailment. The curtailment necessary can be affected by ramping concerns such as those experienced in the late afternoon as solar production decreases and demand increases. An NREL study [4] has found that a mix of wind and solar assets decreases curtailment. The E3 study has shown that diversity decreases over-generation as do other mitigation strategies. These issues along with others (e.g. integration requirements) affect the cost of renewable energy. Diversification of renewable assets has been found to decrease the capital investment and revenue requirements [2].

A report by Lawrence Berkeley National Lab (LBNL) in March 2014 [5] considered the decrease in economic value of variable generation (like that from wind and solar) as penetration levels increase. In high wind penetration scenarios (>40%), geographic diversification of wind resources demonstrated the largest beneficial impact on its value compared to other mitigation strategies [5]. This resulted from increased energy value of the wind used and higher capacity value, and a decrease in the effect of forecast errors. When wind and solar are combined in high-penetration scenarios, they each tend to beneficially affect the value of the other compared to using one or the other alone. Simply put, diversification of resources and diversification of the location where they come from continually demonstrates an improvement in the electricity produced and thus its value. When limited to wind alone, the study [5] found that "the largest increase in the value of wind comes from increased geographic diversity."

Although there appears to be a growing consensus on the apparent benefits of geographic diversification, work remains to further clarify its benefits. This report picks up where the Phase 1 report [3] ended. In this report, data from Wyoming (wind tower data) and California (actual production and consumption) are considered in order to further support the case for resource diversification. Where the earlier report [3] quantified diversity itself, this study seeks to demonstrate a means for quantifying and valuing the benefits of renewable resource diversity by using scenarios involving Wyoming's high capacity factor wind and renewable resources from California. Aside from being specific to Wyoming and California, this report differs from past efforts in that it attempts to provide metrics for evaluating different renewable energy strategies. As a result, it complements other past studies that primarily considered the benefits of tapping into Wyoming's higher wind capacity factors, such as a recent NREL report [6]. The current study uses the scenarios that were provided in the NREL report, and thus should be considered to be complementary to the analysis presented there.

The approach used here is to use wind tower data from sites in Wyoming to estimate wind plant output from several locations. Existing data from California, including wind production, solar production, system demand, and electricity pricing are used in several different analyses. These analyses include estimation of Renewable Energy Quality Metrics (REQMs) that have been developed to assess the performance of a combination of renewable resources. The value of these REQMs is then demonstrated using several examples that highlight the beneficial effects of good resource combination on lowering variability, reducing cost, decreasing storage requirements, and lowering of greenhouse gas emissions and water consumption. Results are provided for the addition of new resources to a large group of existing renewable resources (relevant for a large system operator) as well as for addition to a small group of renewable resources (relevant for a utility). The results shown here demonstrate that, at least for the scenarios considered here, diversifying resources (both type and location) first is good practice for the electrical generation and delivery industry from the perspective of the metrics developed here.

The Concept of Diversity in Renewable Energy

Although briefly discussed above, the idea of diversity is introduced here. The primary concern with integrating renewables into our power system is that their output is variable, which can impair grid stability and reliability, as opposed to conventional power generation that can be precisely controlled. The diversity concept takes advantage of different renewable resources producing energy at different times. By using a diverse set of variable resources, the variability of the supply can be significantly reduced. Diversity can be achieved by either using different sources of renewable energy (e.g. wind and solar) or the same resource at physically different locations. The first type of diversity is called resource diversity, whereas the second is called geographic diversity. The least diverse case is realized when using all of one resource from a geographically limited area.

The benefits of diversity and a lower variability energy supply are many. While energy forecasting errors at a single location may be large (e.g., the wind is not as high as forecast), these errors tend to cancel out as the number of resources increase. The lower aggregate variability translates into lower swings in the supply making the smaller and longer duration variations easier to deal with from an operating point of view. Diverse resources also produce a given level of power more often making their combined output more dependable. The lower aggregate variability can also reduce the power supplied by thermally-generated backup power, thereby lowering the greenhouse gas emissions and water usage. In this report, the definition of a set of metrics for assessment of variable resources is provided, and the metrics are applied to different groups of resources to demonstrate how they may be used for a quantitative comparison. An estimation of tangible benefits like those listed above is then made for different groups of resources.

It should be noted that the real benefits from diversification are very dependent on the existing electrical generation and the variable resources being added. As such, this study only provides a first demonstration of the benefits of diversity, and studies focused to a particular groups (utility, operator, etc.) needs would need to be done to identify the benefits for that group. Nonetheless, the variability of a given renewable energy source is a liability that should be considered when planning which sources to add to an existing system and where best to locate them.

Data Used for the study

Wyoming Wind Data

Meteorological tower data from four Wyoming locations in South Central and East Central Wyoming were provided by Power Company of Wyoming and Pathfinder Wind for use in this study. Ten minute averages from multiple anemometers on the tower at different heights were used to estimate the wind speed at 80 m. To accomplish this, the velocity u - height h relationship given by

$$\frac{u}{u_0} = \left(\frac{h}{h_0}\right)^{\alpha} \qquad (1)$$

was used with the wind data at different heights to determine the exponent α, where u_0 is a reference velocity at reference height h_0. Using this exponent, the velocity at h=80 m hub height was determined using Equation 1.

Period of Wind Considered

Although many years of tower data were available, only a one year period was used in this study. The decision of which year to use was determined by the overlap between the Wyoming wind data and the data from California. Data from June of 2012 to May of 2013 were thus selected. To ensure that this was not an atypical period, wind speed data from the airport in Laramie, WY located centrally to all the wind sites were used to assess long term trends. Figure 1 shows data from this location for four years as well as the eight-year average. The period considered in this study is highlighted in blue. As is evident from the figure, the wind during this period of time was fairly typical. As such, it is expected that the results here are representative of those one would obtain if considering longer time periods.

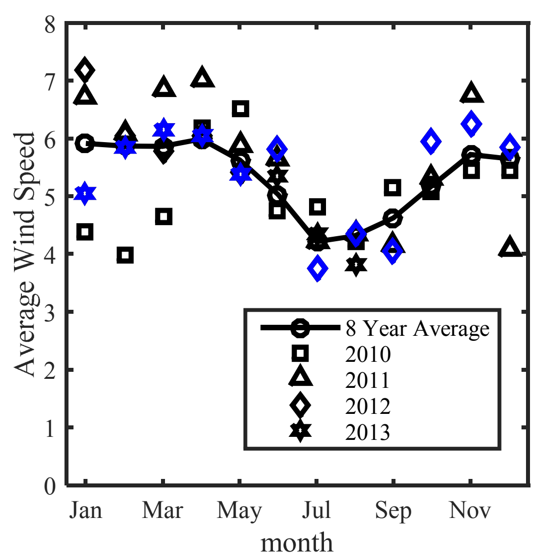


Figure 1-Wind speeds from a nearby airport and the 8 year average. The points highlighted in blues represent wind speeds for the time period considered in this study.

CAISO Data

To determine the diversity benefits of combining Wyoming wind with California renewables, data from California were necessary. The data used for this study were obtained from the California Independent System Operator (CAISO) and consisted of five different types of data, for which the details can be found in reference 7. First, data were acquired for several wind and solar installations so local effects could be assessed. These data, obtained directly from CAISO personnel, were provided in 1 minute intervals, and were averaged to provide 10 minute intervals to match the Wyoming wind data. Second, wind and solar production for the entire CAISO system was obtained to provide a statewide integrated view of production. These data were taken from installations located in both Northern and Southern California. These data also came directly from CAISO in 1 minute intervals, and were averaged over 10 minutes. To investigate potential economic impacts, pricing information was obtained. The Locational Marginal Prices (LMP) for the Mira Loma substation (located near Riverside, CA) were used as representative pricing, and the data were available every 5 minutes, but were averaged to 10 minutes for consistency with the other data. Finally, to consider wind forecasting, the day ahead market forecast was used, and these data were provided in 1 hour intervals. For more details about the data available, please refer to Appendix A.

Analysis Approach

Before the benefits of diversity are discussed, the analysis approach used including the definition of the Renewable Energy Quality Metrics are discussed.

Conversion of wind to power

In order to estimate the power from a wind plant located near to the Wyoming-based wind towers from which the wind data were obtained, wind turbine power information provided by General Electric was used with the hub height velocity determined from the wind tower data as given by Equation 1. A series of power curves for different densities were used as discussed in IEC Standard 61400-12-1 [8] to convert the 10 minute wind speed at 80 m to power. The number of turbines at a site was then adjusted to size the wind plant as needed for a specific analysis. Details of this process are discussed in Appendix B. To account for availability, the power was de-rated by 3% assuming a 97% availability. In addition, a 5% line loss was assumed for the power delivered to California.

Correlations, Energy, Power, and Capacity Factor

Correlations were performed between the different sites in Wyoming and California. Using site pairs with low correlations indicative of diversity, monthly and diurnal wind speeds and power production estimates were used to demonstrate the benefits of diversity. Determination of correlations and power production is discussed in more detail below.

Joint statistics between sites are the primary means used to quantify diversity. The cross correlation of the wind power density between the two sites $R_{p_1 p_2}$ was calculated using

$$R_{P_1 P_2} = \frac{1}{N} \sum_{i=1}^{N} P_i(x_1) P_i(x_2)\ , \qquad (2)$$

and a corresponding cross correlation coefficient $\rho_{p_1 p_2}$ was defined here as

$$\rho_{P_1 P_2} = R_{P_1 P_2} / (R_{P_1 P_1} R_{P_2 P_2})^{1/2}\ , \qquad (3)$$

where P_1 and P_2 are the powers from the wind farms at the different sites identified by x_1 and x_2, and N is the number of instances that are used in the determination of R. Equation 2 is equivalent to the cross-correlation function at zero time lag as defined in reference 9. When the correlation coefficient is one, the power outputs at the two locations follow each other exactly (perfectly correlated). When the correlation coefficient is zero, the power outputs at the two sites are uncorrelated. The lack of correlation between two sites, which is the desired case for diversity, is beneficial in that the wind is not the same at the same time at the two locations as that introduces larger variations into the system.

Rather than showing the actual power produced by a wind farm, it is often more convenient to present the results as capacity factors,

$$C_p = \frac{Actual\ Power}{Maximum\ Possible\ Power}. \qquad (4)$$

Presenting the data this way allows for an easier comparison of sites with different amounts of installed capacity. The capacity factor can be an instantaneous quantity or an averaged quantity.

To demonstrate the concrete benefits of choosing sites with diverse wind resources, the combined power production of different sites was considered. The time history of production was integrated over time to determine energy production E,

$$E = \sum_{i=1}^{N} P(u_i) \Delta t, \qquad (5)$$

where $P(u_i)$ is the wind farm power at velocity u_i, Δt is the time between velocity samples (10 minutes in this case), and N is the number of velocity samples used to determine E. The average power $\bar{P}$ was determined using

$$\bar{P} = E / \sum_{i=1}^{N} \Delta t. \qquad (6)$$

Renewable Energy Quality Metrics (REQMs)

Aside from more standard parameters used to discuss renewable energy production, other metrics are proposed here that provide information that complements metrics such as the capacity factor. This is necessary since capacity factor alone does not fully describe a renewable resource or, perhaps more importantly here, the combination of renewable resources. Because the resources being considered here are unsteady, additional quantities that characterize the varying production are required. Figure 2 shows a histogram of the power output (normalized by the maximum output) of a combination of renewable resources, including wind, solar, and geothermal sources. In the remainder of this section, the quantities highlighted in the figure will be used in the definition of the quality metrics.

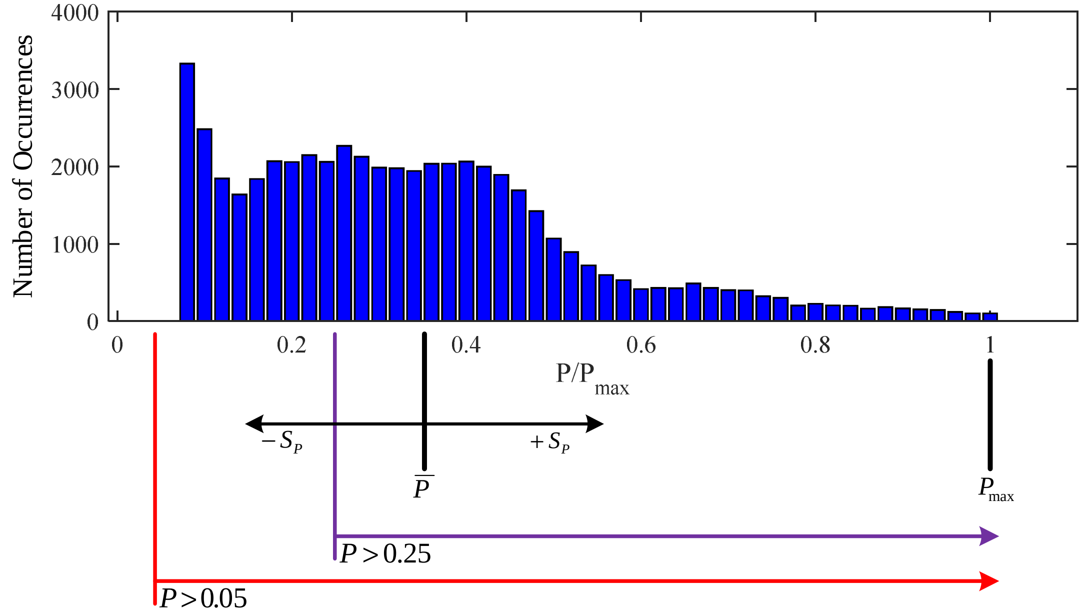


Figure 2 – Histogram of 10 minute power output from a combination of different renewable resources for one year. For reference, several of the quantities relevant to the Renewable Energy Quality Metrics are shown.

Capacity Factor Metric

In the context of quality metrics, the capacity factor is used to describe the energy production of a given site relative to the energy it would produce were it operating at full capacity over the entire period under consideration. The capacity factor can be expressed in terms of power as the average power normalized by the installed capacity

$$C_p = \bar{P}/P_{max}. \qquad (7)$$

Both the average power $\bar{P}$ and installed capacity P_{max} are identified in Figure 2.

Relative Variability Metric

The relative variability RV is a measure of how variable the power of a source is relative to the average power it produces

$$RV = S_P/\bar{P}, \qquad (8)$$

where the standard deviation S_P and the average power $\bar{P}$ are shown in Figure 2. The lower the variability of the renewable resources, the more consistent their output, and thus the uncertainty of the production is reduced. If the uncertainty is reduced, benefits such as the lower likelihood of a large departure from estimated output requiring the use of higher operational cost resources are gained. Thus lower variability sources are considered better than higher variability sources.

Producing Power Metric - Power Greater than 5% Capacity

Another measure of importance in renewable energy systems is how often they are actually producing power. Thus, another metric has been defined to measure the time a group of renewable sources is producing. To quantify this metric, it has been defined as the probability that the power produced is greater than 5% of capacity

$$P > 5 = Probability(P > 0.05P_{max}), \qquad (9)$$

where $P > 5$ represents this metric, P is the instantaneous power, and P_{max} is the installed capacity. When $P > 5$ is high, it represents a renewable energy system that is producing power much of the time, and, when it is low, it represents a system that is idle much of the time. Thus, a high value for $P > 5$ is considered positive for renewable energy systems. As shown in Figure 2, the region represented by $P > 5$ captures all of the 10-minute power output from this group of renewable resources. The group of resources in this figure includes geothermal power that is assumed to be producing all the time, which accounts for the value of 1 for $P > 5$ in this case.

Producing Significant Power Metric - Power Greater Than 25% Capacity

To complement the metric that quantifies how often a renewable energy system is producing power, $P > 5$, another metric was needed that quantifies how often the system is producing a significant amount of energy. For this purpose, the probability that the power produced is greater than 25% of installed capacity was selected

$$P > 25 = Probability(P > 0.25P_{max}), \qquad (10)$$

where $P > 25$ represents this metric, P is the instantaneous power, and P_{max} is the installed capacity. This metric is a measure of production availability in that, the more often it is producing a significant amount of power, the more the asset can be depended upon for supplying electricity to the grid. When $P > 25$ is high it represents a system that producing significant power much of the time, whereas a low value represents a system that has low or no output most of the time. As a result, a high value for $P > 25$ is a positive metric for a renewable energy system. Figure 2 shows graphically the region of production captured by this metric, which indicates that $P > 25$ is far less than 1 for this case.

Use of the REQMs

Unlike capacity factors that just indicate the average power produced by a given set of renewable resources over a given period of time, the relative variability metric RV, the producing power metric $P > 5$, and the producing significant power metric $P > 25$ quantify how often that power is being produced. As such, they complement accepted measures such as capacity factor and thus provide a means of comparing how diversity improves the dependability of the power produced.

Diversity Impacts

To demonstrate the effects of resource diversification in practical terms, the effect of diversification on three characteristics of energy production, prices, CO_2 emissions, and water consumption, are considered. The way in which the differences in energy production were determined and how that affects the energy production characteristics are described below.

Differential Power Production and Impact

The differential power is determined by determining the production for two different scenarios and then taking the signed difference between the two. Integrating this difference over time provides a measurement of the difference in energy produced between the two sites. This energy difference can be converted into changes in cost, CO_2 emissions, and water consumption using approaches outlined below.

Cost

To estimate the impact on price, the power difference was multiplied by the electricity pricing data discussed above to determine the cost difference.

CO2 Emissions

To determine the CO_2 emissions, the emission per unit energy produced (lbs CO_2/MWh) is required. This is obtained by multiplying the average heat rate (Btu/MWh) for a power plant by the Carbon Dioxide uncontrolled emission factor (lb CO_2/million Btu) for natural gas.

Using averages for 2012 [*10*], the heat rate for a natural gas fired power plant is 8.039 Btu/MWh, and the uncontrolled emission factor is 117.1 lb CO_2/million Btu yielding a CO_2 emission rate for natural gas produced electricity of 941 lbs CO_2/MWh.

While CO2 emissions reductions attributable to renewable energy diversification are included in this study, it is noted that reductions in other criteria pollutant emissions should also be achieved by reducing the cycling of thermal combustion based power plants compensate of renewable energy electricity generation variability .

Water Consumption

The electrical energy production industry is a large user of water. More than 40% of all extracted fresh water is used for thermoelectric power operations – mostly for cooling purposes [*11*]. Additional water is consumed if carbon sequestration and storage are used [*11*]. To determine a water consumption rate appropriate to address electrical power related water savings in California, water consumption rates for natural gas fired electricity, the most likely source to be used in lieu of renewables, were used. Of the natural gas fired power plants in the United States, 80% are Natural Gas Combined Cycle (NGCC) power plants, and 80% of those rely on recirculating cooling systems

[*12*]. Reference 11 provides water consumption estimates for different types of electricity power production, including NGCC plants with recirculating cooling systems. Such plants consume between 130 and 300 gallons/MW-hr with a median usage of 200 gallons/MW-hr, which is the value used in this study.

Storage

One of the major impacts of decreased variability in the power supply would be on the amount of storage required. One challenge for increased deployment of storage is its cost [*13*]. For example, the installed cost of a pumped hydro storage facility per MW is more than 5 times the cost of building a natural gas fired turbine.[2] The cost of storage is also related to its capacity. Pumped hydro storage is the most inexpensive storage technology today with a capacity cost for storage of $90-150/MW-hr [*14*]. With other storage technologies significantly higher than this, any reduction of storage that can be achieved using diverse energy production would directly translate into cost savings.

To determine the storage need for a given combination of renewable resources, a simplified approach was taken. Storage was assumed to be sufficient so a prescribed power profile could be met with renewable resources alone. The power profile was assumed to provide 50% of average power for 8 hours of the day, and 125% of average power for the remainder of the day. The storage was assumed to be half full at the beginning of the period considered. When power supply exceeded demand, energy was added to the storage unless it was at full capacity. When power supply fell short of demand, energy was taken from storage to meet demand. The storage size was then adjusted until the power needs were just met over the interval considered (e.g. storage never fell below zero at any time during the period). To provide representative examples, two months of the year with different production characteristics were chosen: December and June.

Scenarios

To provide concrete benefits of Wyoming wind energy in the California market, several scenarios were considered. Each of the combinations is described below.

Wyoming Wind and California Wind and Solar

To contrast Wyoming wind and California wind, several examples are provided that combine power estimated for Wyoming wind plants with existing California wind plants. Such comparisons allow for assessing each wind plant as well as combinations of their output. Also provided are examples that combine power estimated for a Wyoming wind plant with the aggregate wind on the CAISO system.

[2] http://www.eia.gov/todayinenergy/detail.cfm?id=6910

These examples demonstrate the benefits of using power generated by Wyoming wind either by itself or in combination with a California wind plant. In addition, a scenario that is relevant to a utility or regional operator is considered, where the addition of a wind or solar plant from California to one existing solar and one existing wind plant is considered and compared with the addition of one Wyoming wind plant.

Wyoming Wind and California Renewables (NREL 33% Scenario) Incremental Addition

A second scenario combines power estimated for Wyoming wind plants with a mix of renewable resources provided in a recent NREL publication [6] called here the CA 33% or CA/WY 33%. Table 1 provides the capacity, annual generation, and capacity factors for the 33% portfolio additions outlined in the document. The amount of capacity of each resource was chosen such that the annual production is 12000 GWh [6]. Examples that use this scenario demonstrate the benefits of using Wyoming wind by itself or in conjunction with California renewables.

Table 1 – NREL 33% Scenario [6]. The California mixture has been reduced to three categories for the current analysis.

	CA 33%			CA/WY 33%		
Technology	Capacity (MW)	Ann. Gen. (GWh)	Capacity Factor	Capacity (MW)	Ann. Gen. (GWh)	Capacity Factor
CA Geo/Bio	513	3642	0.810			
CA Solar	2563	6297	0.280			
CA Wind	757	2061	0.311			
WY Wind				3000	12000	0.457

Wyoming Wind and California Renewables (NREL 33% Scenario) Addition to Existing California Renewables

The final scenario combines power from either Wyoming wind or California renewables in the 33% portfolio additions as given in Table 1 to existing California renewable production. These three scenarios are referred to as CA Exist, CA + CA 33%, and CA + CA/WY 33%. Examples that use this scenario identify the benefits of adding Wyoming wind to the existing California renewable production. The mix of resources for this scenario is summarized in Table 2.

Table 2 – Existing CA renewable resources with additional capacity added according to the NREL 33% scenario [6] as given in Table 1.

	CA Exist		CA + CA 33%		CA + CA/WY 33%	
Technology	MW	%	MW	%	MW	%
CA Geo/Bio	800	9.6%	1313	10.8%	800	7%
CA Solar	4000	48.2%	6563	54.1%	4000	35%
CA Wind	3500	42.2%	4257	35.1%	3500	31%
WY Wind	0	0.0%	0	0.0%	3000	27%

Results

The results of performing the analysis on the data described in the previous section are presented here. Correlations between Wyoming wind-generated power and that from California are performed to confirm the results found in the Phase 1 study [3] that was based on modeled data. Comparison of seasonal and diurnal variations of California and Wyoming wind resources is then provided to demonstrate why the resource diversification identified by the correlations is effective. Next, the quality metrics presented earlier are determined for the various scenarios discussed above to quantify the benefits of diversifying renewable resources. Finally, the impact of introducing renewable resource diversity into the California market is discussed. A crude assessment of economic, greenhouse gas, and water savings is presented, and examples of when having Wyoming wind assets on the CA grid might have avoided price spikes are given. Finally, the impact of diversity on storage required to meet a demand curve using renewable resources alone is considered.

Correlations

A primary result of the Phase 1 Study [3] was that locations with good diversity could be identified using the correlation coefficient given in Equation 3. In that study, the correlations were calculated from wind speeds obtained from weather simulation models. Here, the correlations are determined between actual power output from wind farms in California and power output from potential wind farms in Wyoming estimated from velocity data from meteorological towers as described above. The results of this analysis are presented in Table 3, where combinations of output from Wyoming and California wind sites are given. As is evident from the table, when Wyoming locations are combined with Wyoming locations or California locations are combined with California locations, the resulting correlation coefficients are relatively high when compared to those values obtained when Wyoming locations are paired with California locations. Lower correlations are considered to be good indicators of diversity, which implies that a given resource will better complement the resource against which they are being correlated. This result essentially confirms the results of the Phase 1 study and suggests that correlations should be used as a screening criteria when initially picking sites to combine.

The correlations in Table 3 are useful for choosing which wind assets to combine together when choosing a group of resources. More important in many applications is the correlation between a new location and the present resources on the system. To demonstrate this application of the correlation, different wind resources in California and Wyoming were correlated with the aggregate wind on California's system as shown in Table 4. Here it is clear that the correlations between Wyoming wind locations and California's aggregate wind are much lower than those of individual California wind sites correlated with aggregate California wind. This lower correlation suggests that the diversity indicated by the lower correlations would suggest that Wyoming wind would better complement existing California assets than would additional California wind.

Table 3 – Correlation coefficients for power produced for various combinations of wind installations in California and Wyoming. The California power was obtained from actual wind farms, whereas the Wyoming power was estimated from wind tower data. The numbers highlighted in light green are Wyoming-Wyoming correlations, those in light blue are California-California correlations, and those in bright green/blue are California-Wyoming correlations.

		WY				CA					
		WY 1	WY 2	WY 3	WY 4	CA 1	CA 2	CA 3	CA 4	CA 5	CA 6
WY	WY 1	1.000									
	WY 2	0.783	1.000								
	WY 3	0.760	0.748	1.000							
	WY 4	0.755	0.732	0.891	1.000						
CA	CA 1	0.479	0.507	0.463	0.493	1.000					
	CA 2	0.549	0.593	0.572	0.584	0.503	1.000				
	CA 3	0.475	0.540	0.518	0.545	0.572	0.560	1.000			
	CA 4	0.534	0.613	0.570	0.578	0.650	0.526	0.719	1.000		
	CA 5	0.519	0.574	0.560	0.569	0.625	0.519	0.737	0.927	1.000	
	CA 6	0.467	0.488	0.444	0.472	0.899	0.518	0.553	0.622	0.600	1.000

Table 4 – Correlation coefficients for power produced from existing California wind and wind sites in California and Wyoming.

	WY				CA					
	WY 1	WY 2	WY 3	WY 4	WF 1	WF 2	WF 3	WF 4	WF 5	WF 6
CA Wind	0.574	0.627	0.600	0.622	0.779	0.631	0.864	0.911	0.931	0.786

Monthly and Diurnal Variations in Capacity Factor

Although geographic diversity of wind resources is often discussed as a means of improving the quality of wind-generated electricity, concrete examples of this diversity make it easier to understand how diversity has an impact. The fundamental concept of diversity is that different locations produce power at different times such that the overall production is more consistent. One way of demonstrating these diversity benefits is by considering seasonal and diurnal behavior of wind generated power. The variation by month of the capacity factor of one of the Wyoming locations is compared with that of the total wind power on the CAISO system in Figure 3. As is evident in this figure, one of the phenomena that is providing diversity is the difference in the seasonal variations in the wind: California wind peaks in the summertime, whereas Wyoming wind peaks in the winter. Overall, the combination of these resources produces a more consistent output than either one alone. The results also stress that adding more California wind would likely just continue to make the variation worse, and thus increase the difficulty of using the power from an operations point of view. Results for additional locations in Wyoming that show similar behavior are provided in Appendix C – Monthly capacity factors – Wyoming Sites and Aggregate California Wind.

A similar type of behavior is observed if the diurnal variation of the capacity factor is considered. Figure 4 shows the hourly power output averaged over the year for a Wyoming installation and that from all wind on the CAISO system. Again, it is clear how diversity causes these two resources to complement each other. The figure shows that the California wind peaks at night, whereas Wyoming wind peaks in the late afternoon and stays relatively high through the early evening hours.

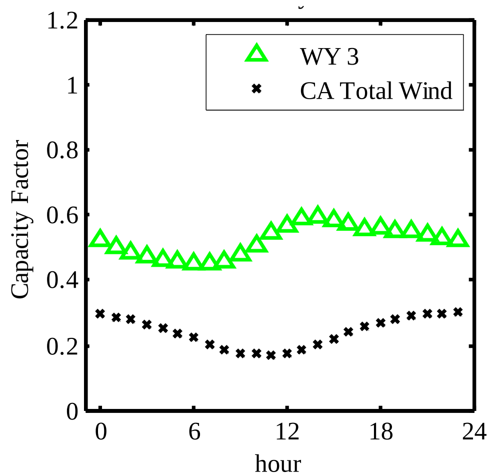


Figure 3 – Monthly average capacity factors for California's wind generation and that for a site in Wyoming. The Wyoming and California wind peak at different times of the year indicating seasonal diversity of the winds.

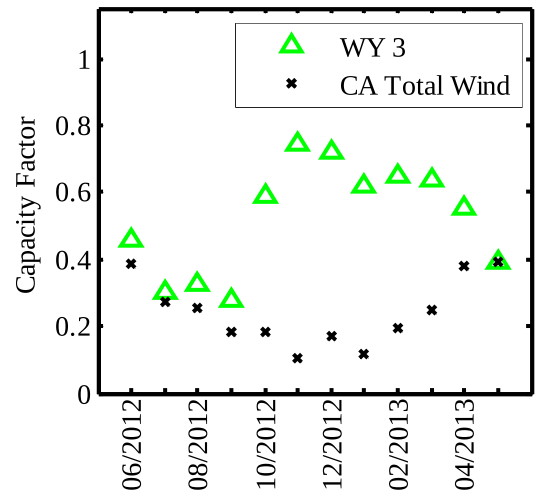


Figure 4 – Hourly average capacity factors for California's wind generation and that for a site in Wyoming. The Wyoming and California wind peak at different times of the day indicating hourly diversity of the winds.

Interplay of Renewables - Seasonal

Although these seasonal and hourly results are interesting, they are averaged over too long of periods to allow drawing any general conclusions since it is the instantaneous relationships between power sources that are critical. As a result, this analysis is broken down further into diurnal variations at different times of the year. Figure 5 shows the hourly variation of wind speeds again, but now only averaged over different seasons. The exact three-month periods chosen were selected to highlight the differences of the wind in different time periods. In the November-January time frame, it is evident that the capacity factor that results from both Wyoming and California resources is not varying much diurnally. Wyoming's resource is at its highest production, whereas California is at its lowest. Later in the year, February – April, there is more diurnal variation in both Wyoming and California production, and California's production has increased considerably. Note that the phasing of the two sources is good at this time – Wyoming's production is increasing while California's drops with the opposite also true. In the May-July period, the two sources are producing similar amounts of power, but the phasing between the two is still shifted in a beneficial way. Finally, the August-October time frame shows Wyoming output at its lowest with California's wind starting to drop, but peak production is still offset. In summary, at all times of the year, these two resources appear to complement each other in a positive way.

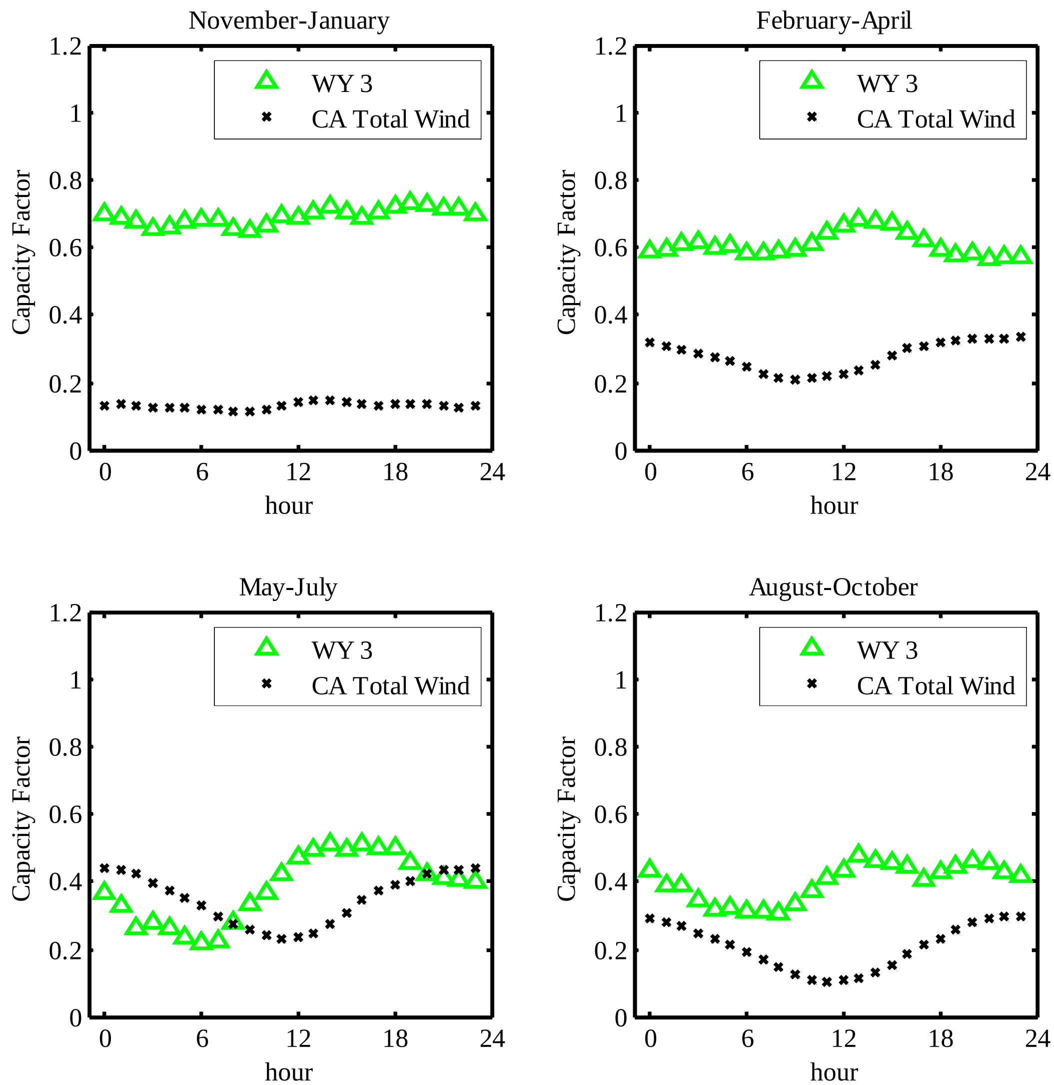


Figure 5 – Hourly average capacity factors for California's wind generation and that for a site in Wyoming at different times of the year. For all seasons, the Wyoming and California winds appear to complement each other, although the nature of the winds vary significantly throughout the year.

Renewable Energy Quality Metrics (REQMs) for Different Scenarios

It appears from the results provided above that there are some real benefits to diversifying wind resources to provide a better end product, the delivered electricity. What is missing is a means of quantifying which system is better. In this section, the REQMs discussed in the Renewable Energy Quality Metrics section are applied to the cases given in the Scenario section. These scenarios consider a wind-wind comparison, a Wyoming wind versus a California renewables comparison, and a comparison of adding incremental Wyoming wind to California's existing renewables versus adding more California renewables. This broadens the consideration of just wind resources to wind, solar, geothermal and biomass resources in this case. The results suggest that the approach used here provides a means of quantifying a resource and enables comparison of different approaches to meeting electricity demand using new renewable installations coupled with existing renewable and non-renewable resources.

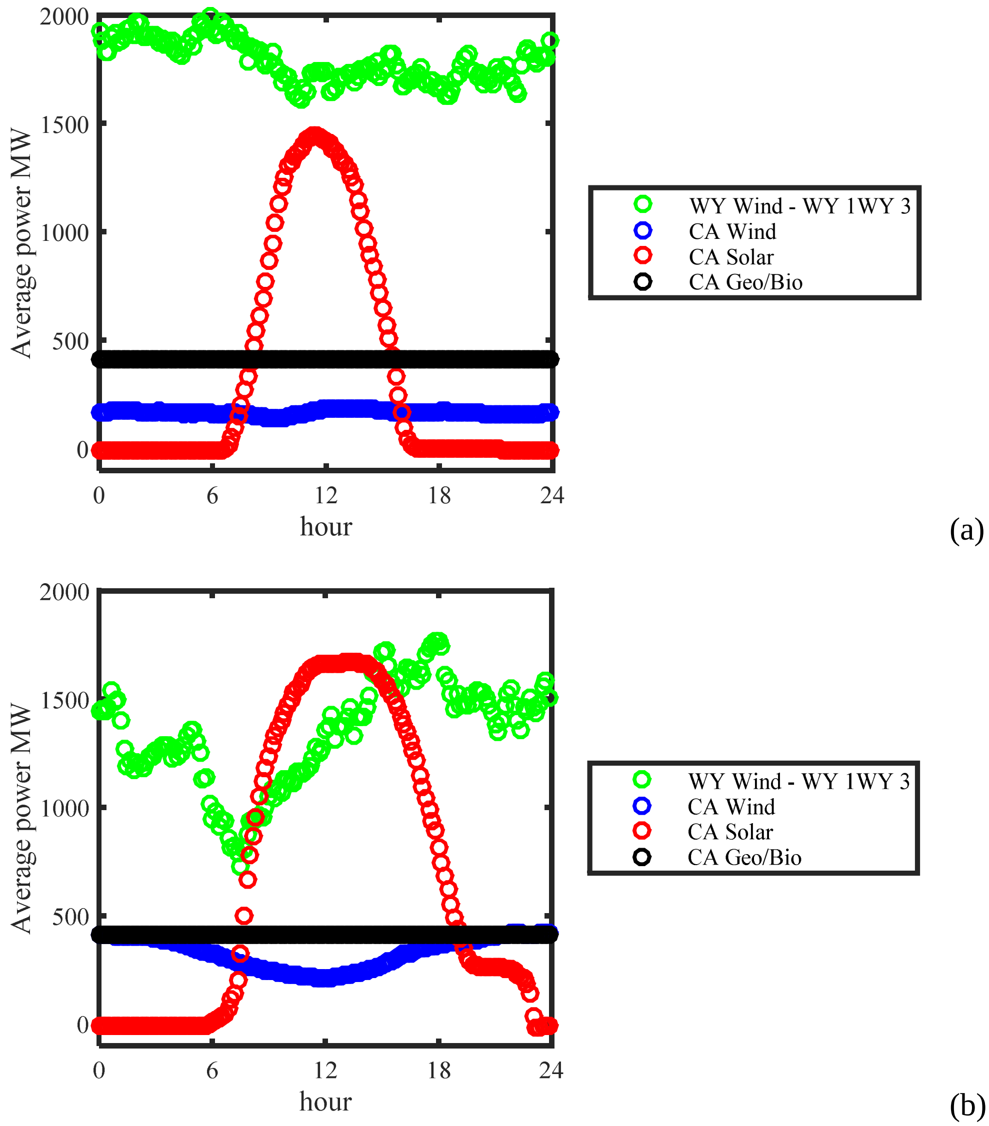


Figure 6 – Monthly average hourly output of different resources in the NREL 33% Scenario: (a) December, and (b) June.

Before considering the metrics determined, the renewable assets that will be considered are discussed. Figure 6 shows the hourly average output of the assets described in Table 1 and referred to as the NREL 33% Scenario. The production by these sources is estimated using the wind tower data in Wyoming as described previously along with the output history of California's renewables, all scaled to the levels given in Table 1. Results are shown for one winter month in Figure 6(a) and for one summer month in Figure 6(b). Similar patterns in the Wyoming wind production are observed to those discussed previously: relatively constant production in the winter (on average) and more variable production in the summer. The high dependence of solar power on time of day is depicted, as is the assumed constant output of geothermal/biomass production. Below the quality metrics for different scenarios are determined.

WY Wind – CA Wind and Solar

The first comparison of REQMs is made among different options for adding Wyoming and California wind to the grid. Adding all of the incremental capacity from 1 site is compared to splitting that same addition between 2 or more sites. As shown in Table 5, the widely used capacity factor behaves as expected in that it is simply the weighted average of the component wind resources. However, capacity factor does not capture how the combination of the two resources provides a more stable output or not. As a result, the relative variability RV is considered. In all cases, it is observed that, as different assets are added, the relative variability decreases well below that of any one wind resource. If the resources are more diverse, the decrease is greater. As discussed in the metrics section, a lower variability indicates that a group of resources has reduced production uncertainties relative to those with higher variability. As can be seen here, the relative variability decreases 50-100% depending on the combination of assets chosen relative to using one source alone.

The other aspect of this analysis is the ability to directly compare different combinations of assets. For instance, if someone were trying to choose the best asset to combine with the CA 3 wind site, an evaluation can be made on a quantitative basis. From Table 5, it is shown that adding just the CA 5 site decreases the relative variability slightly, while adding either WY 1 or WY 3 resource nearly halves the variability.

The other two performance metrics, $P > 5$ and $P > 25$, both support diversity and quantify its effects. In Table 5, it is observed that the relative amount of time that the resources are producing power ($P > 5$) increases from 65-80% of the time to >90% of the time when assets are combined. Similarly, the relative amount of time the resources are producing significant power ($P > 25$) increases from 40% with one California asset to 65-70% when combined with on Wyoming asset. As a tool to make decisions, the results here would suggest that combining CA 3 with WY 3 would be the most advantageous as it has the best combination of quality metrics of combining CA3 with any other wind farm.

Table 5 – Performance metrics for combinations of two sites in California and two sites in Wyoming.

% Installed Capacity				Capacity	Relative	P>5%	P>25%
CA 3	CA 5	WY 1	WY 3	Factor	Variability		
100%				0.240	1.03	0.67	0.39
	100%			0.266	1.08	0.62	0.41
		100%		0.440	0.81	0.80	0.59
			100%	0.482	0.77	0.79	0.64
50%	50%			0.242	0.97	0.71	0.40
50%		50%		0.333	0.61	0.91	0.64
50%			50%	0.359	0.61	0.90	0.67
	50%	50%		0.342	0.65	0.89	0.64
	50%		50%	0.371	0.64	0.89	0.68
		50%	50%	0.462	0.65	0.90	0.71
25%	25%	25%	25%	0.340	0.54	0.95	0.69

Although useful as an illustration, wind is not always competing just with other wind sites in resource development. Consider the case where a utility has limited existing wind and solar assets and is considering adding more. How does the utility best judge what resources to add from the many choices available? Table 6 shows the performance metrics when one additional 100 MW plant is added to an existing portfolio of one 50 MW wind plant (CA 2) and one 50 MW solar plant (CA 4). Adding wind from an additional California site (CA5) improves all the metrics slightly, with the relative variability decreasing significantly (by 21%). In contrast, adding power from one California solar site (CA 5) significantly degrades all the performance metrics. Adding wind from a Wyoming site (WY 1 or WY3) outperforms all other combinations with all performance metrics improving: relative variability decreases (29%), while capacity factor increases (up to 41%) as do the $P > 5$ and $P > 25$ metrics (17% and 42% respectively) due to the high quality of Wyoming's wind. Such comparative results allow a utility to select what resource work best with the existing resources already on their system. For example, adding more California solar would be a poor choice in this case, when, in comparison, adding Wyoming wind would yield a 50% higher capacity factor, a 41% lower relative variability, and an 86% higher $P > 25$.

Table 6 – Performance metrics for 50 MW of wind and 50 MW of solar from two specific sites in California and those resulting from the addition of one wind or solar plant. California wind sites are highlighted in green, California solar sites are highlighted in yellow, and Wyoming wind sites are highlighted in blue.

Installed Capacity (MW)						Capacity	Relative	P>5%	P>25%
CA 2	CA 5	CA 4	CA 5	WY 1	WY 3	Factor	Variability		
50		50				0.266	0.85	0.77	0.47
50	100	50				0.269	0.67	0.88	0.49
50		50	100			0.250	1.02	0.70	0.36
50		50		100		0.350	0.61	0.93	0.63
50		50			100	0.374	0.60	0.90	0.67

NREL 33% Scenario Incremental Addition Comparison

Another example of the use of the Renewable Energy Quality Metrics (REQMs) is provided by comparing the addition of Wyoming wind generated electricity to California's grid to additional electricity supplied by California's indigenous renewable resources. For this purpose, the 33% NREL scenario given in Table 1 is used. Table 7 shows the performance metrics of the assets alone and in the two proposed combinations: energy supplied by Wyoming wind (WY1 and WY3), and energy supplied by California wind (CA W), solar (CA S), biomass, and geothermal. One cautionary note is that biomass/geothermal (CA G) has been treated as an on-demand resource with 81% capacity factor and no variability. As with the results in the wind-only scenario above, it is observed that the quality metrics improve (except for Geothermal as cautioned above) when going from a single resource (the 100% lines) to combined resources. Interestingly, when combining Wyoming assets (two wind plants), the results are more favorable than the combination of California renewables: the relative variability is lower, and the relative time the combined resources are generating significant power $P > 25$ is larger (71% vs 41%). Only the relative time that the plant is producing any power $P > 5$ is greater for the California mixture due to the constant production of the geothermal resources. This scenario suggests that Wyoming's wind (CA/WY 33%) is a higher quality resource in terms of these quality metrics than the mix of California's renewable resources (CA 33%). These results add to the positive cost-benefit ratio results of the NREL study [6] to indicate that Wyoming wind would be a good addition to California's grid.

Table 7 – Renewable Energy Quality Metrics (REQMs) for the 33% NREL Scenario in Table 1: two wind sites in Wyoming make up the Wyoming contributions, and a combination of wind, solar, and geothermal make up California's contributions. This table only considers the performance of the added capacity. Note that row 3 is representative of the CA/WY 33% resource mix, and row 7 is the CA 33% resource mix.

% Installed Capacity					Capacity Factor	Relative Variability	P>5%	P>25%
WY1	WY3	CA W	CA S	CA G				
100%					0.440	0.81	0.80	0.59
	100%				0.482	0.77	0.79	0.64
50%	50%				0.462	0.65	0.90	0.71
		100%			0.311	0.79	0.82	0.53
			100%		0.280	1.34	0.49	0.38
				100%	0.810	0.00	1.00	1.00
		19.8%	66.9%	13.3%	0.357	0.71	1.00	0.49

NREL 33% Scenario Addition to Aggregate Renewables Comparison

The REQMs results presented in Table 7 considered the addition of renewables without considering the renewable electricity generation already on the California system. To assess the benefits of adding different renewable combinations to the existing system, three assessments of performance metrics were made for the following cases: 1) a simplified version of the existing blend of renewables (CA Exist), 2) the existing blend of renewables plus the NREL 33% scenario of California renewables (CA + CA 33%), and 3) the existing blend of renewables plus the NREL 33% scenario of Wyoming wind

(CA + CA/WY 33%). Table 8 shows the results of these three analyses. Since the addition of more California renewables simply adds more of the same resources, it would be expected that the metrics would stay about the same or worsen a little, which is what is observed in the table. However, by adding Wyoming wind, it is observed that the metrics increase across all categories, once again displaying the benefits of diversity. Despite Wyoming wind contributing just over 25% of the installed capacity, the relative variability decreases over 30% and the time the renewables are producing significant power increases by over 10%.

Table 8 – Renewable Energy Quality Metrics (REQMs) for the 33% NREL Scenario described earlier: two wind sites in Wyoming make up the Wyoming contributions, and a combination of wind, solar, and geothermal make up California's contributions. This table considers the performance of existing California resources with that where either CA resources are added or WY resources are added.

	% Installed Capacity					Capacity	Relative	P>5%	P>25%
Description	WY1	WY3	CA W	CA S	CA G	Factor	Variability		
CA Exist	0%	0%	42.2%	48.2%	9.6%	0.344	0.59	1.00	0.63
CA + CA 33%	0%	0%	35.1%	54.1%	10.8%	0.348	0.62	1.00	0.60
CA + CA/WY 33%	13.3%	13.3%	31.0%	35.4%	7.1%	0.365	0.43	1.00	0.77

This section has quantified the benefits of diversity showing that, for the renewables considered, geographic diversification provides a higher quality product (in terms of the REQMs) when considering wind resources alone, incremental renewable energy additions, and additions of renewable energy in the context of existing renewables on the system. It is suggested that this approach may provide a means for industry and policy makers to quantitatively evaluate which renewable resources to develop.

Economic/Environmental Impact Estimate

The Renewable Energy Quality Metrics (REQMs) for three different scenarios discussed above clearly show that, with respect to these metrics, geographic diversity of resources appears to result in a better electrical product. In this section, an attempt is made to translate these benefits into practical terms: (1) increased energy produced and its value, (2) reduced CO_2 emissions, and (3) reduced water consumption that result from the increased energy production. Two comparisons are made here consistent with the previous analysis. The first comparison uses wind installed in Wyoming and wind installed in California, and the second uses wind installed in Wyoming and an array of California renewables as given by the NREL 33% scenario.

Wyoming and California Wind

For this scenario, the installation of 6000 MW of wind capacity at sites in California and Wyoming is considered in line with the Wyoming/California wind analysis presented in Table 5. The baseline used is the installation of 6000 MW in California at two different sites. Installations that combine a total of 6000 MW at different sites in Wyoming and California are compared to this baseline case. Note that the installation of equal amounts of capacity allows for comparison among the resources to be made while holding capital cost constant. Figure 7 shows a 10 day record of the power output from the baseline case and a case with one California location and one Wyoming location. Two power differences are shown: ΔP_1 where the combined

California/Wyoming power exceeds the all California power, and ΔP_2 where the power from the all California case exceeds that of the California/Wyoming case. To determine the net energy difference, the difference in the power output between the baseline case and the case under consideration was integrated in time. Also shown in the figure is the hour ahead price of electricity during the same time period.

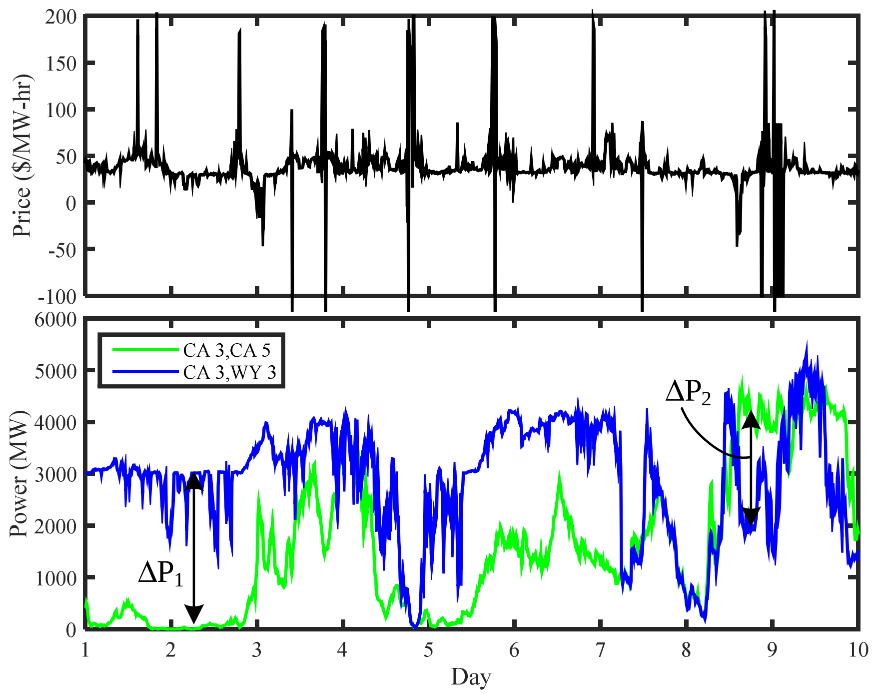


Figure 7 –The 10-day combined output of two California wind plants compared with output of a Wyoming wind plant combined with a California wind plant. Also shown is the hour ahead pricing of electrical power for the same interval.

Using this energy difference, the cost difference, CO_2 emission difference, and the decreased water usage were all calculated over a year using the methods described in the Analysis Approach section. Table 9 shows the results for two wind installations in Wyoming and two others in California, whereas Table 10 shows the results for two wind installations in Wyoming and that for California using the aggregate performance of current California wind assets to estimate output for a given amount of installed capacity. The former table can be considered more relevant to new installations in both California and Wyoming, whereas the latter is more relevant for considering the impact of adding new Wyoming wind to California's existing wind assets. In both cases, significantly more energy is produced when California assets are combined with Wyoming wind assets, partially due to increased capacity factor that Wyoming offers, and partially to geographical diversity. The energy differences in the 1000s of GW-hrs when using Wyoming assets along with California assets produces savings exceeding $100 million dollars annually for the 6000 MW of installed wind considered. To put these numbers in perspective, 1000 GW-hrs is enough energy to power 100,000 homes in the Western U.S. [3] or is equivalent to the output of seventy-five 3.0 MW turbines operating at 50% capacity factor. This extra energy can also be thought of as displacing other generation using fossil fuels and thus reduces the CO_2 released into the atmosphere by millions of tons. A million tons of CO_2 is equivalent to the amount released by 193,000 cars over the course of a year. Finally, the energy difference can also be considered in terms of the water saved in not producing the electricity using gas-fired generation. Under both scenarios considered here, over a billion gallons of water is saved by combining Wyoming and California assets. A billion gallons is enough water to fill 1500 Olympic size swimming pools (660,000 gallons per pool), to irrigate 1325 Acres of farmland for a year (at 2.35 acre-feet of water per acre [15], or provide 8500 average family homes with their annual water needs (116,000 gallons/year[4]).

Table 9 – Annual impact of 6000 MW of installed wind capacity made up of different Wyoming and California wind locations.

Installed Capacity MW				**Annual** Energy Difference GW-hrs	**Annual** Cost Difference Million $	**Annual** CO2 Difference Thousand Tons	**Annual** Water Difference Million gallons
CA 3	CA 5	WY 1	WY 3				
3000	3000			-	-	-	-
3000		3000		5228	166	2444	1046
3000			3000	5850	194	2735	1170
	3000	3000		5204	158	2433	1041
	3000		3000	6002	190	2806	1200
1500	1500	3000		5216	162	2438	1043
1500	1500		3000	5926	192	2770	1185
1500	1500	1500	1500	5604	176	2620	1121

NREL 33% Scenario Incremental Addition Comparison

The NREL 33% scenario capacities were determined to produce the same amount of power, and thus this scenario should show no difference in energy production. However, when the case was run, energy differences in the 1000 GW-hr range were observed. This simply indicates that, for this time period, Wyoming resources were performing a little better than average or California's were slightly under average performance. To address this, the installed capacities were adjusted to produce the same

[3] A annual consumption of 10,000 kW-hrs was assumed based on the 2009 Residential Energy Consumption Survey (RECS)

[4] Reduce Your Outdoor Water Use, EPA-832-F-06-005, May 2013, http://www.epa.gov/WaterSense/pubs/outdoor.html

amount of energy under either the CA 33% or the CA/WY 33% Scenario. In this case, there was still a cost difference in the $5 million dollar range. Although this number is not as significant as the cost differences given for the scenario above, it is using pricing from the 2012-2013 time frame over which this study was conducted. As solar capacity grows, pricing will change and thus this analysis should be extended to future pricing scenarios for a better estimate of the true economic impact of diversity. It should be pointed out that, while significant, this cost difference will be small compared to the reduction in capital cost afforded by Wyoming's higher capacity factors.

Table 10 – Annual impact of 6000 MW of installed wind capacity made up of different Wyoming and California wind locations. California wind is estimated using the current output of CA wind assets.

Installed Capacity MW			**Annual** Energy Difference GW-hrs	**Annual** Cost Difference Million $	**Annual** CO2 Difference Thousand Tons	**Annual** Water Difference Million gallons
CA	WY 1	WY 3				
6000			-	-	-	-
3000	3000		6140	195	2870	1228
3000		3000	7413	243	3466	1483
3000	1500	1500	6749	216	3155	1350

Case Studies of Particular Events

To provide some specific examples of the impact of adding diversity to California's renewable energy mix, events that triggered very high prices due to ramping events that were not forecast during the time period of the study were identified, and many appear to be linked to what is happening with the wind on the system at the time the price spikes occurred. Consider Figure 8 that shows the forecast and actual output of wind on the CAISO system on March 6. Also shown is a representative price as discussed in the section above discussing CAISO data. The estimated output of 3000 MW of wind located in Wyoming is shown for comparison. During the afternoon, the output from the wind resources dropped by nearly 1500 MW in less than 6 hours when only a slight decrease in power was forecast during this time. The decrease happened as electricity demand increased in the afternoon and as solar resources were decreasing. Towards the end of this period, the price spikes selling at over $200/MW-hr for more than an hour. Although higher spikes are observed in the price data (10 minute values of $2000/MW-hr happen at times), the length of the sustained increase in price here is of interest. During this same time, it is observed that the Wyoming wind was actually increasing a sufficient amount to essentially offset the entire drop experienced by California's wind resources. As such, diversifying resources could help reduce the impact of forecast errors on such ramping events and thus reduce costs.

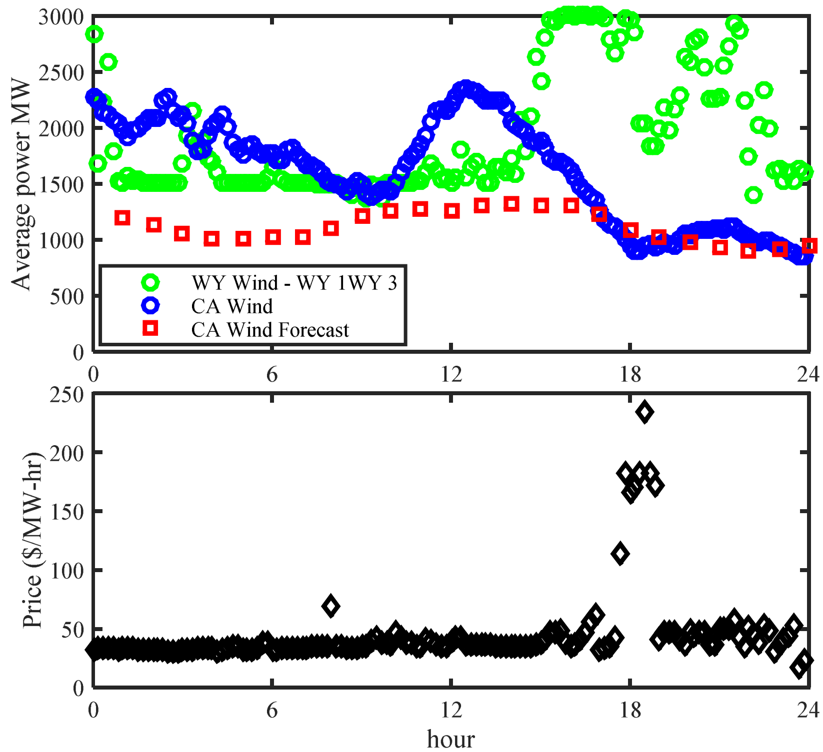


Figure 8 – Wind-generated electricity and that forecasted with the LMP pricing at the Mira Loma substation on March 6, 2013. Also shown is the estimated output from 3000 MW of Wyoming wind.

Storage

In order to demonstrate the impact of diversity on storage requirements, simulations of a storage system were run using scenarios including California's existing renewable resources with and without the resource additions given in the NREL 33% scenarios. As discussed above, a simplified demand curve requiring 50% of average power output between 10 PM and 6 AM and 125 % of average power the remainder of the time was used. Simulations run for the months of December and June provide representative cases for different times of the year. All of the simulations were performed as described in the Diversity Impacts section. The starting storage was varied until the storage met demand at all times. Example results obtained from these simulations are shown in Figure 9 and Figure 10 for the months of December and June for the case where the capacity additions for the two 33% NREL scenarios are added to existing California renewable resources. As evident in Figure 9, which represents the 33% NREL case using all California resources (CA + CA 33%), the strong diurnal variation in output has a small impact on the larger storage picture compared to the longer time variations. What appears to be a combination of low solar and wind production in the middle of the month draws down stored energy supply before it rebuilds toward the end of the month. In contrast, Figure 10, which represents the addition of Wyoming Wind to existing California resources (CA + CA/WY 33%), shows a larger wind component, although the diurnal effects of solar are still visible. For most of the month, the storage stays relatively constant, but low wind at the end of the month causes the storage to drop dramatically at that time.

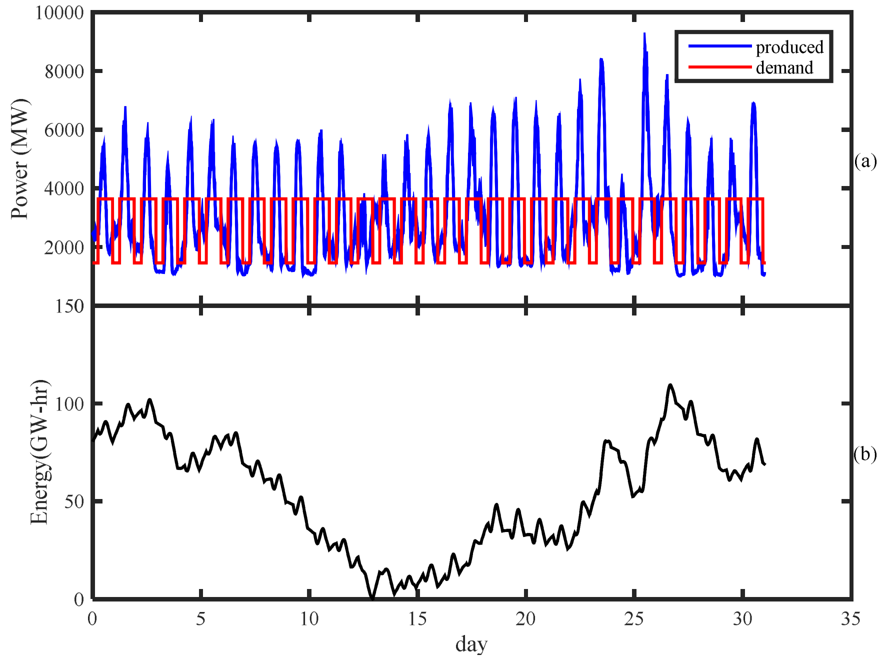


Figure 9 – Energy storage results for existing CA renewable resources and additional CA renewable resources (CA + CA 33%) specified by the NREL 33% scenario for the month of December 2012: (a) combined resource production as well as the demand curve, and (b) storage profile.

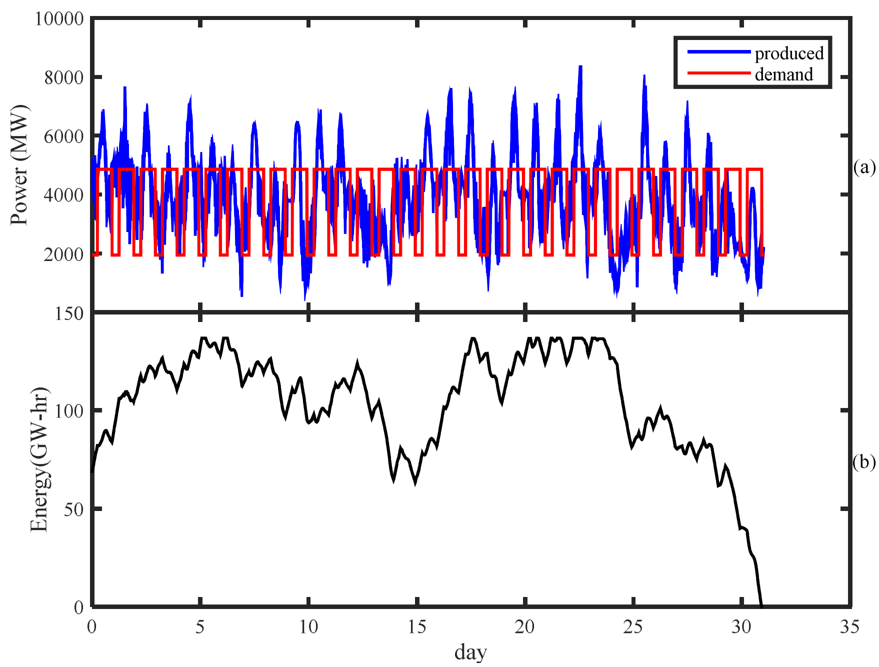


Figure 10 – Energy storage results for existing CA renewable resources and added Wyoming wind resources (CA + CA/WY 33%) as specified by the NREL 33% scenario for the month of December 2012: (a) combined resource production as well as the demand curve, and (b) storage profile.

The tabulated results for the cases presented in Figure 9 and Figure 10 (CA + CA 33%) as well as for existing California renewables (CA Exist) and the NREL 33% case using Wyoming wind (CA + CA/WY 33%) are given in Table 11 for the month of December and in Table 12 for the month of June. The storage is characterized by providing the starting, ending, and maximum energy stored as well as the system capacity (considered to be twice the stating storage). In addition to characterizing the storage requirements, the total energy generated for that month and the ratio of Maximum storage required to total generation are given. The storage/generation ratio (the rightmost column in the tables) is perhaps the best comparison of these cases as it removes the effects of having different average powers (and thus total energy generated) for the different cases.

Table 11 – Energy storage results for December for existing CA renewable with and without additions from California and Wyoming based on the NREL 33% scenarios.

	Installed Capacity (MW)					Storage December (GW-hrs)				Total Generation	Storage/
Description	WY 1	WY 3	CA W	CA S	CA G	Capacity	Start	End	Maximum	(GW-hrs)	Generation
CA Exist	0	0	3500	4000	800	123.4	61.7	53.9	88.5	1473.0	0.0601
CA + CA 33 %	0	0	4257	6563	1313	160.8	80.4	68.9	109.4	2176.6	0.0503
CA + CA/WY 33 %	1500	1500	3500	4000	800	136.6	68.2	0.0	136.6	2909.0	0.0471

Table 12– Energy storage results for June for existing CA renewable with and without additions from California and Wyoming based on the NREL 33% scenarios.

	Installed Capacity (MW)					Storage June (GW-hrs)				Total Generation	Storage/
Description	WY 1	WY 3	CA W	CA S	CA G	Capacity	Start	End	Maximum	GW-hrs	Generation
CA Exist	0	0	3500	4000	800	109.2	54.6	37.1	109.2	2344.4	0.0467
CA + CA 33 %	0	0	4257	6563	1313	132.2	66.1	45.3	132.2	3383.5	0.0391
CA + CA/WY 33 %	1500	1500	3500	4000	800	117.8	58.9	21.6	117.8	3374.4	0.0351

The addition of CA renewables to existing California resources (CA + CA 33%) is observed to reduce the storage/generation ratio compared to existing CA renewables (CA Exist) in both tables. This is primarily a result of the addition of significant amount of geothermal/biomass capacity. However, it is observed that the addition of Wyoming wind (CA + CA/WY 33%) produces an even greater reduction of the storage/generation ratio. This is entirely a result of the complementary nature of Wyoming wind and California's existing renewable resources and the demand curve provided. As a result, this scenario provides a concrete demonstration of the benefits of diversity. This is particularly impressive when the percentage of high capacity factor geothermal is much lower for the CA + CA/WY 33% scenario (7.1%) than for the CA + CA 33% scenario (10.1%).

Considering both June and December results suggests that overall storage requirements are lower if Wyoming wind incorporated into California's renewable energy mix. Table 13 and Table 14 show the storage required for 1000 GW-hrs of generation in December and June, respectively. Note that 1000 GW-hrs is the average amount of energy produced monthly under additions specified in the NREL 33% scenario. As indicated in the tables, the amount of storage required is lower with new California resources, but still lowers more with the addition of Wyoming wind. Thus, it is clear that, with the addition of power from just one outside source, the amount of storage capacity required is 10% less, with even lower requirements achievable if a more diverse set of resources was used. For a grid scale system, this represents a significant reduction of investments required, even if the cost of energy storage drops. Assuming a levelized cost of storage of $500/MW-hr, the monthly cost of storage equates to $20-30 million dollars. On an annualized basis, the savings due to using Wyoming wind (CA + CA/WY 33%) rather than all California resources (CA + CA 33%) is anticipated to be in the 70-80 million dollar range. Of course, such simulations should be performed using actual capacity mixes and demand profiles to get savings relevant to a particular configuration. In addition, the simulations should be carried out over several years so that longer term trends (seasonal variations) are captured. Nonetheless, it is believed that similar conclusions will result from those more detailed studies. If California is successful at deploying less expensive storage, the savings would be reduced from the levels quoted here.

Table 13 - Energy storage requirements for 1000 GW-hrs of energy generation for December for existing CA renewables with and without additions from California and Wyoming based on the NREL 33% scenarios.

Description	Monthly Storage GW-hrs	Monthly Storage Cost millions of $	Annualized Storage Cost millions of $
CA Exist	60.1	30.05	360.6
CA + CA 33 %	50.3	25.15	301.8
CA + CA/WY 33 %	47.1	23.55	282.6

Table 14 - Energy storage requirements for 1000 GW-hrs of energy generation for June for existing CA renewables with and without additions from California and Wyoming based on the NREL 33% scenarios.

Description	Monthly Storage GW-hrs	Monthly Storage Cost millions of $	Annualized Storage Cost millions of $
CA Exist	46.7	23.35	280.2
CA + CA 33 %	39.1	19.55	234.6
CA + CA/WY 33 %	35.1	17.55	210.6

Conclusions

An analysis of combining renewable energy assets from California and Wyoming has been carried out to determine the benefits of geographical diversity of renewable energy assets. To accomplish this, wind data from meteorological towers in Wyoming were combined with production data from California. The current results support those of an earlier study that only used modeled data in that both studies found a beneficial decrease in correlations between favorable sites and evidence of diversity in diurnal and seasonal production. To enable quantification of diversity benefits, Renewable

Energy Quality Metrics (REQMs) for evaluating a group of renewable assets were developed. In terms of these quality metrics, combining high capacity factor Wyoming wind with California's existing renewable resources outperformed the sole use of California assets in all categories. To demonstrate meaningful benefits of renewable resources with better REQMs, the impacts on energy production, energy cost, greenhouse gas emissions, and water use were all demonstrated. In addition, how diversity could eliminate price spikes from large scale ramping events that require flexible capacity resources was shown. Finally, the likelihood that diversity could decrease the amount of storage required was demonstrated using a simplified analysis.

The results clearly show that, in nearly all cases considered here, geographic diversity has the potential to enhance the characteristics of the electrical generation and distribution systems (see the sidebar). Specifically, Wyoming wind when combined with California's own renewables provides a better electrical product (as characterized by the REQMs) than California's indigenous renewables alone can provide. Only two wind locations in Wyoming were needed to show significant improvements. With the Renewable Energy Quality Metrics (REQMs) presented here, different scenarios can be tested providing additional information for decision makers from utilities, policy making bodies, and system operators to aid in their decisions about which combination of renewables available to them provide the best characteristics when added to their current system. From a regional operations perspective, this capability is believed to be increasingly important as these regions move from a maximum of 20-30% penetration of renewables to higher levels as it provides the means of identifying the renewable energy resources that allow for increasing the amount of renewable energy used while reducing negative impacts in pricing and operations. From the smaller scale perspective of a utility or electrical cooperative, these REQMs allow for an objective means of identifying which additional renewable resources work best with the limited existing resources already on their system. The ability to reduce the amount of storage needed to provide a given level of backup/firming for a system by developing transmission arteries that allow for full geographic diversity is an intriguing finding.

Diversity Benefits

- Improved grid operability
- Reduced flexible capacity requirements
- Reduced storage requirements
- Fewer curtailments
- Lower greenhouse gas (GHG) emissions
- Lower water use

Because this report used data from 2012 and 2013, it must be considered that the results would change if updated data were used. In particular, the growth of indigenous renewable resources in California's energy portfolio would provide a different set of answers than those found here. However, considering the results that have been shown, it is expected that the integration of Wyoming wind into current California renewable resources would have an even more beneficial effect than that discussed here. In particular, the growth of solar energy in California has changed both hourly energy production levels and corresponding prices such that this analysis should be repeated with newer data to update the results presented here.

This report only considered one specific diversification focus: the addition of Wyoming wind energy to California's renewable energy production. If further diversification is considered (wind from other sites in the West combined with other renewables from outside California), the performance of renewable sources (as characterized by the REQMs) on the entire Western grid should only get better. This suggests that an optimum solution will be achieved only as the geographical area over which electricity from renewable resources is shared increases. Eliminating existing barriers to regional sharing of renewable assets and eventually moving toward a regional and interconnect-wide solutions will allow for the best use of our variable renewable resources as they begin to produce large fractions of our electrical energy supply. This conclusion is in line with suggestions by the Union of Concerned Scientists [16] for addressing grid integration in California: diversifying the renewable resources used and increasing the coordination of assets over larger regions can provide flexible generation reserves and decrease curtailment thereby lowering the cost of integrating renewables.

Clearly, this report and its predecessor are only a demonstration of the possibilities of geographic diversity. It should not be mistaken that diversity alone can address all the challenges facing the electricity industry today, but, in combination with other strategies (e.g. storage and demand response), diversity should aid in improving the ability to effectively incorporate renewable resources into the grid. To further demonstrate the impact of resource diversity, simulations over longer periods of time using data from a large number of sources (some of which are hard to obtain) are clearly needed. Simulations by system operators and utilities looking to enhance their mix of renewables would be particularly interesting in that these groups have access to the types of data required to perform a complete analysis and the perspective to interpret the importance of the results in the context of the overall needs of the electrical generation and distribution problem.

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Appendix A - CAISO Data Details

Wind and solar data from individual installations in California were provided directly by CAISO personnel. Aggregate wind and solar production for the entire CAISO system was provided in the same way.

Other data, including the wind production forecast and electricity pricing, was directly downloaded from CAISO's OASIS web site.[5] Pricing data were obtained using the Interval Locational Marginal Price found under Prices for the entire period of this study, June 2012-May 2013. Wind forecast data were obtained from the Wind and Solar Forecast found under System Demand. Pricing information only overlapped the present study period for January-May 2013, and thus the analyses for which these data were used could only be carried out during this period. Details of what information is provided in these files may be found in reference 7.

[5] http://oasis.caiso.com/

Appendix B - Turbine Power Curve and Conversion from Wind Speed to Output Power

A series of power curves were obtained for a specific industrial grade wind turbine for different densities. When the density fell between two of these power curves, simple interpolation was used to determine the power for a specific wind density and velocity. When the density fell below the lowest density for which a power curve was given, then the wind speeds for the power curve were adjusted using [8]

$$V_{pc,\rho} = V_{pc,\rho_0}\left(\frac{\rho_0}{\rho}\right)^{1/3},$$

where $V_{pc,\rho}$ is the corrected power curve velocity at density ρ, and V_{pc,ρ_0} is the velocity for the known power curve at density ρ_0. Velocity measurements at density ρ are then used to determine the power produced.

Appendix C – Monthly capacity factors – Wyoming Sites and Aggregate California Wind

The monthly capacity factors at various locations in Wyoming are compared to the aggregate capacity factor of the total California wind resource. The complementary nature of the production is obvious in all four locations shown. Wyoming wind has good capacity factors all year with a peak in production in the winter months. This complements California's wind that has its peak production in the summertime with relatively small production during the winter. It should be noted that winter, when Wyoming's wind is at its highest, is also the lowest production period for California solar.

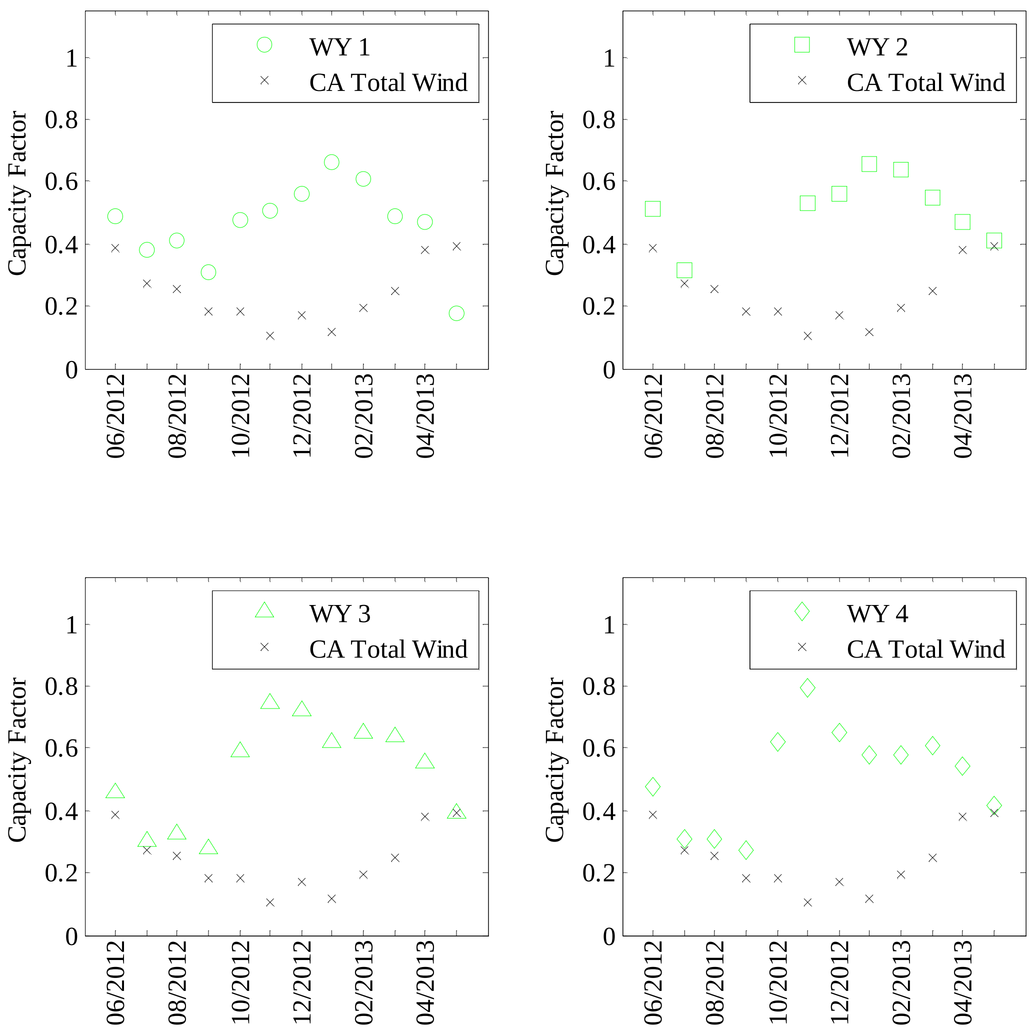

Figure 11 - Monthly average capacity factors for California's wind generation and that for sites in Wyoming. The Wyoming and California wind peak at different times of the year in all cases indicating seasonal diversity of the winds.