Arnold Schwarzenegger
Governor

INTERMITTENCY ANALYSIS PROJECT: CHARACTERIZING NEW WIND RESOURCES IN CALIFORNIA

PIER INTERIM PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Transportation

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Abstract

The State of California intends to greatly expand the use of renewable energy sources for generating electric power. Intermittent resources such as wind energy, when deployed in large quantities, can create significant challenges for utility system operations. The California Energy Commission (CEC) initiated the Intermittency Analysis Project (IAP) to address this issue by studying the impacts of large amounts of new wind generation on the reliability, operation, and economic performance of the California Bulk Power System (CABPS). AWS Truewind, LLC, was engaged by the CEC to simulate the output of existing and future wind projects as an input to grid impact analyses to be performed by GE Consulting. This report describes the methods employed by AWS Truewind for this purpose, presents sample results, and compares the results to data obtained for existing wind projects.

Executive Summary

AWS Truewind was engaged by the California Energy Commission (through a subcontract to the University of California at Davis) to provide simulated wind plant output data in support of the Intermittency Analysis Project (IAP). AWS Truewind's role was to identify and characterize a large number of potential sites for new wind projects, simulate three years of hourly wind generation from both existing and proposed new projects, simulate next-day and four-hour-ahead hourly wind generation forecasts, and produce samples of one-minute output data for representative or significant time periods.

In the first step, AWS Truewind selected 233 sites representing both existing and potential new wind projects in 14 wind resource areas. The sites were chosen to maximize mean plant output (derived from the California wind map), after considering various factors such as distance to the existing transmission grid, protected areas, and slope. The sites were allocated to three scenarios: the existing scenario, 2010 scenario, and 2020 scenario.

For each site, AWS Truewind then simulated the plant output on an hourly basis for the three years from 2002 to 2004. The calculations take into account the evolution of wind turbine technology, including the existing mix of old and new turbines, state-of-the-art turbines under the 2010 scenario, and hypothetical turbines to be developed in the future under the 2020 scenario. AWS Truewind also simulated four-hour-ahead and next-day wind plant forecasts for each site for the same time period, based on experience with wind forecasts in California. Finally, AWS Truewind produced samples of one-minute plant output data for a number of representative and significant periods within the three years.

By comparing the simulated data with actual data from operating wind projects in the state, AWS Truewind confirmed that the simulated data provide a realistic picture of the dynamic and stochastic behavior of wind projects and wind forecasts.

1.0 Introduction

AWS Truewind was engaged by the California Energy Commission (through a subcontract to the University of California at Davis, subcontract XXX) to provide certain wind-energy data in support of the California Energy Commission's Intermittency Analysis Project (IAP). The objective of the Intermittency Analysis Project is to assess the impacts of a substantial expansion of wind generation on the reliability, operation, and economic performance of the California Bulk Power System (CABPS). The scenarios of wind generation include over 10 gigawatts (GW) of new wind production capacity, in addition to the existing capacity, which totals about 2 GW. AWS Truewind's role was to:

- identify and characterize a number of sites for prospective new wind energy projects sufficient to satisfy the expansion scenarios in 11 focus areas of the state;
- simulate three years of hourly wind generation from both the existing and proposed new wind plants;
- simulate next-day hourly wind generation forecasts for the same plants;
- produce samples of one-minute output data for significant or representative times.

These data were used by GE Consulting to assess the impacts of wind generation on various aspects of the CABPS's operations and costs. This work is described in a separate report. The present report describes the methods, assumptions, and results of AWS Truewind's portion of the project.

2.0 Project Approach

AWS Truewind's work for the IAP consisted of four main tasks:

(1) definition of wind scenarios and selection of candidate wind project sites;

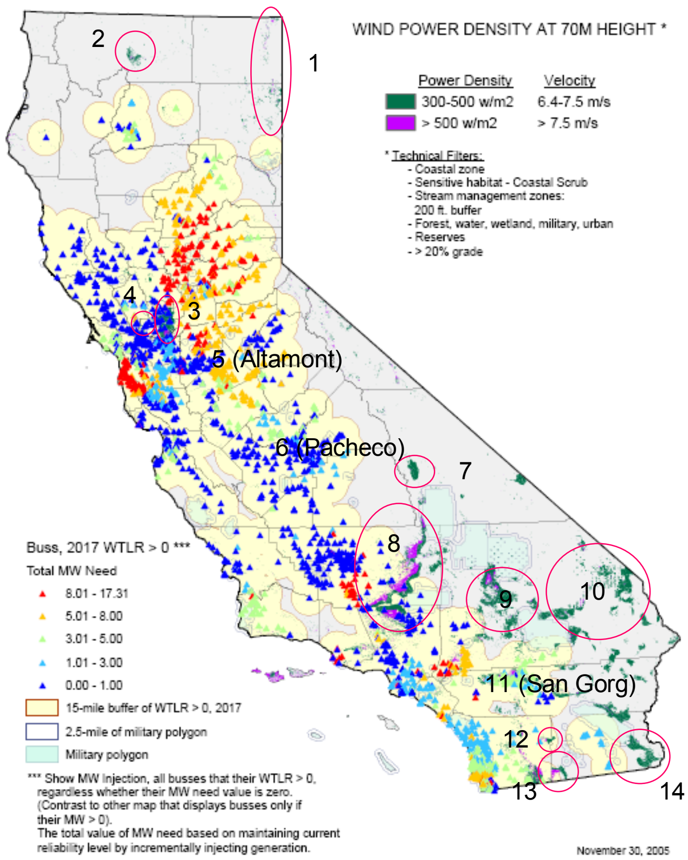
(2) simulation of hourly wind generation;

(3) simulation of next-day forecasts; and

(4) simulation of one-minute samples of wind generation. The approach to each task is described below.

2.1. Site Selection

The selection of candidate wind project sites started with a map of 11 focus areas for new projects defined by others on the IAP team. Figure 1 presents the map showing the focus areas as provided to AWS Truewind. The labels and numbers were added by AWS



Statewide – 11 new areas of interest

Figure 1. Eleven areas of interest for new wind generation capacity (pink ovals) and three existing resource areas (Altamont, Pacheco, and San Gorgonio Pass)

Truewind, and include three existing wind resource areas – Altamont Pass, Pacheco Pass, and San Gorgonio Pass. Due to existing deployment and growth constraints in the region, these three existing wind resource areas were evaluated for 2010 development but not for significant new wind projects in the 2020 scenario. (The area numbers therefore run from 1 to 14 rather than from 1 to 11.)

Within the focus areas, we selected about 300 plausible sites for new wind projects, each at least 100 megawatts (MW) in size, representing a total potential wind capacity of about 34 GW. These sites formed a pool from which the sites required to satisfy any particular wind scenario could be chosen. The sites were selected using custom site-screening methods and software developed by AWS Truewind. These tools have been applied successfully in a number of regions of the US and Canada as well as other countries to help developers identify attractive sites for wind projects. The site-screening process followed these steps:

- The predicted mean wind speed at 80 m height was extracted for each site from the California wind map, which was created in a previous project by AWS Truewind using its MesoMap system.[1]

- Modeled wind speed distributions and air density were used to predict the average annual energy output of the GE 1.5sle turbine, which was judged typical of its class, assuming normal rates of turbine and plant downtime and electrical, wake, and other losses. The result was a map of the predicted net average annual capacity factor throughout the state, from which a mean net capacity factor was extracted for each site.

- Exclusion zones were identified and mapped. They included federal and state forests and parks, locations within 1 mile of any dwelling or populated area, water bodies, and slopes greater than 20%, as well as areas outside the 11 focus areas.

- The existing transmission grid was overlaid on the state, and the distance and cost to build a new line connecting any point to the existing grid was estimated. The paths avoided the exclusion zones (except steep slopes). Costs for transformers to boost the line voltage to the existing grid voltage were added.

- Using the data layers created up to this point, a site-screening program developed by AWS Truewind was run. This program scans a region and identifies contiguous or near-contiguous clusters of grid cells capable of supporting wind projects of a desired minimum size at a cost of energy (COE) lower than a specified threshold. The COE threshold is adjusted to yield the desired number of sites. The COE includes estimates of the installed cost, interconnection cost, net capacity factor, and operations and maintenance costs, however, the results are not very sensitive to these assumptions as sites are selected and ranked according to relative, not absolute, COE. The result was a map of 302 sites distributed among the 11 new focus areas and a table summarizing their characteristics (including latitude and longitude, mean speed, net capacity factor, project area, and nearest interconnection point).

- With the site map and table, and working in consultation with GE Consulting and other IAP participants, AWS Truewind whittled down to a number judged sufficient to satisfy the requirements of two scenarios, denoted the 2010 and 2020 scenarios. For the 2010 scenario, AWS Truewind selected 42 sites representing about 5900 MW of new wind capacity; for the 2020 scenario, 134 sites

[1] AWS Truewind, LLC, "New Wind Energy Resource Maps of California," Report to the California Energy Commission, Contract #500-01-009 (2002).

representing about 14,800 MW of new wind capacity were chosen. Combined, the sites totaled about 20,700 MW of potential new wind capacity.[2]

- Fifty-seven additional sites were selected from the master list (or added manually if outside the 11 new focus areas) to represent about 2100 MW of currently operating wind projects.
- AWS Truewind assigned each of the sites in the 2010 scenario, as well as each of the existing wind project sites, to a bus number from a list of buses produced by other members of the IAP team. Each bus corresponds to an entry point for wind energy on the CABPS. In many cases several sites were assigned to the same bus. GE Consulting used these bus assignments as a guide in selecting sites for their grid simulations. AWS Truewind did not make bus assignments for sites in the 2020 scenario, since for most of the sites there are no existing buses that could accept the additional generation, and new transmission investments will be required.

2.2. Hourly Wind Generation Profiles

In the next stage of the analysis, AWS Truewind created, for each existing and future site identified in the previous stage, hourly simulated wind generation data spanning the period January 1, 2002, to December 31, 2004. The data were derived in the following procedure:

- AWS Truewind's mesoscale weather model, MASS, was run in nested grids covering the state for the three year period, using a variety of weather data sources (reanalysis, rawinsonde, and surface) as inputs, and the predicted winds, direction, temperature, and surface pressure were stored hourly for each grid point and for several heights above ground. The horizontal spatial resolution of the simulations was 8 km, which was judged sufficient to simulate key features of the wind climate in the main wind resource areas of the state.
- For each site in the site list, a time series of speed, direction, temperature, and pressure were extracted from the nearest mesoscale grid point. The speeds were then scaled so that the average speed matched the expected mean derived from the California wind map; this step adjusted for the limited spatial resolution of the mesoscale simulations. (The California wind map provides mean speed estimates on a 200 m grid, which accounts for the local effects of small-scale

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[2] The IAP team did not assume that the scenarios would necessarily occur in the named years. Rather the names were created as a shorthand to describe scenarios with differing levels of wind penetration. Furthermore, the megawatt totals of the sites selected by AWS Truewind do not necessarily match those in GE Consulting's grid impacts analysis, as GE Consulting constructed different scenarios by selecting subsets of sites from the list according to capacity targets in each region.

topography and surface roughness changes.) At the same time, the temperature and pressure were combined with the site elevation to estimate air density in each hour.

- The speed, direction, and density data were then combined with an appropriate turbine power curve (described below) to estimate gross and net plant output for each hour. In the process, typical wind plant losses, including wake losses, blade soiling, high-wind control hysteresis, turbine availability, and electrical losses, were accounted for. The average total loss was about 14%, with a typical range of 11% to 16%. The effect of turbulent wind fluctuations on plant output was also simulated, and the output values were time-filtered to mimic the spatial averaging of fluctuations in large wind projects.
- For sites in one of the existing wind resource areas in the state (Altamont, Solano, Montezuma Hills, Pacheco, Tehachapi, and San Gorgonio), the monthly and diurnal averages were adjusted to correct for any discrepancies between the simulated and observed patterns.

The turbine power curve assumed for each site depended on the site's location and wind resource and on the scenario. For existing wind projects, AWS Truewind employed an effective plant power curve derived from observed plant output and speed data. The purpose of this was to match the observed average output and patterns of behavior of existing projects – which include many different turbine models from different eras – as closely as possible. For new projects in the 2010 scenario, the average of three commercial turbine power curves was employed. The turbine models were chosen according to the IEC class of the site.[3] For Class I sites, the mix included the GE 1.5sl, Vestas V80, and Gamesa G80 turbine models. For Class II sites, the mix included the GE 1.5sle, Vestas V82, and Gamesa G87 models. For Class III sites, the GE 1.5xle, Vestas V100, and Gamesa G90 models were employed.

Last, for the 2020 scenario, a theoretical power curve defined by turbine specific power (in watts-per-square-meter of swept area) was employed.[4] For Class I sites, a specific power of 350 W/m^2 was assumed; for Class II sites, the assumption was 300 W/m^2; and for Class III sites, 250 W/m^2. The 2010 and 2020 power curves are depicted in Figure 2.

[3] Turbines are designed for sites that fall within a range of wind conditions defined by the IEC class. At a standard sea-level air density of 1.225 kg/m^3, a site is Class I if its mean speed exceeds 8.5 m/s, Class II if it exceeds 7.5 m/s, and Class III if it is below 7.5 m/s. The speed threshold is adjusted according to the air density: a lower air density means the speed threshold for a particular IEC class can be increased, so that, for example, a Class II turbine could be used at a site that, at standard density, would be Class I.

[4] Power curves provided by Kevin Jackson, consultant to the CEC.

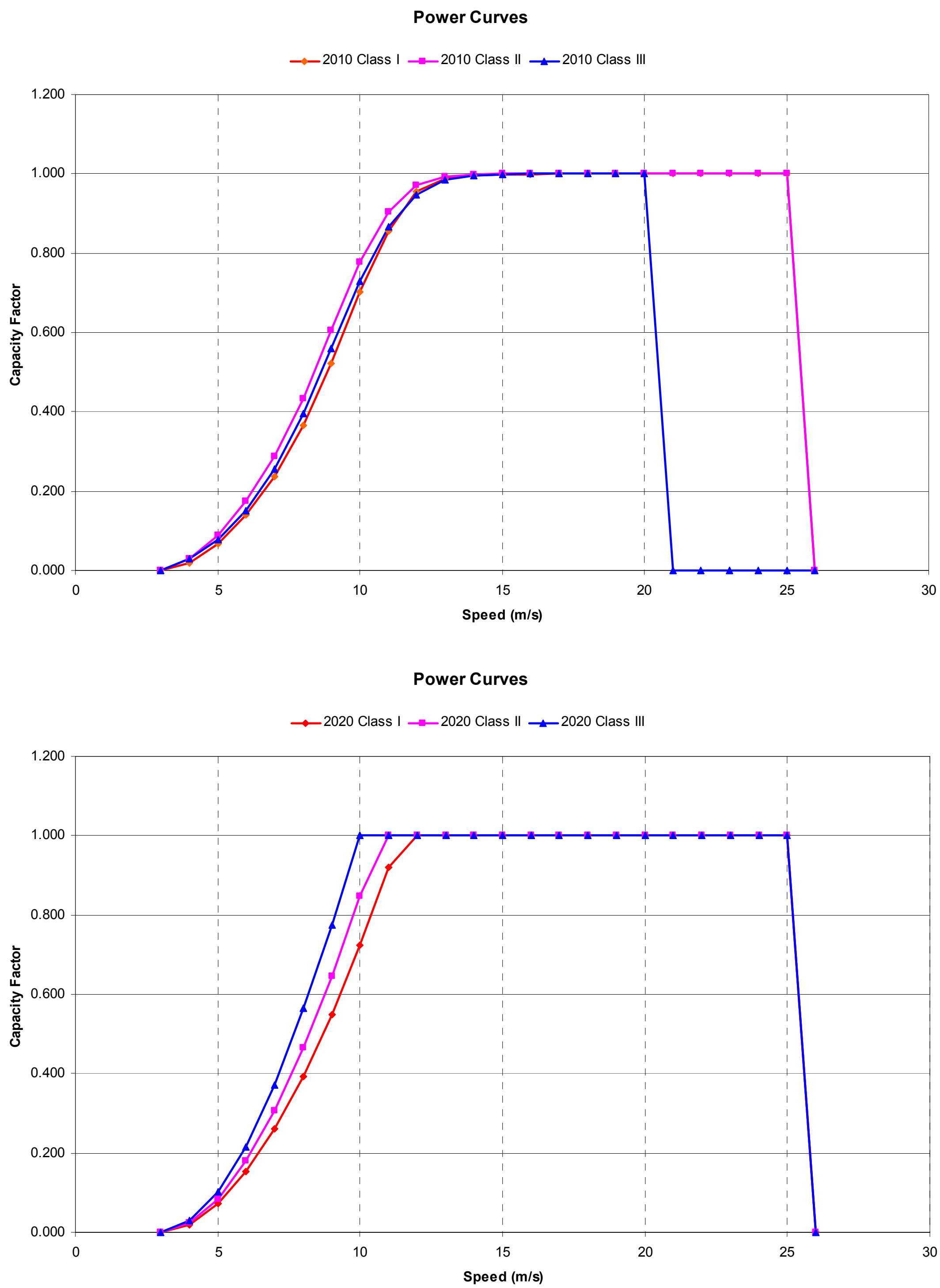


Figure 2. Composite power curves (normalized power output as a function of wind speed) by IEC site class (I, II, or III) for (a) 2010 scenario and (b) 2020 scenario.

2.3. Forecasts

After producing the hourly generation data, AWS Truewind simulated forecasts for the existing and future wind project sites. The aim was to reproduce the dynamic behavior and error patterns of state-of-the-art wind forecasts, as represented by AWS Truewind's eWind forecasting service, which provides forecasts for numerous wind projects in the state including projects participating in the California Independent System Operator's (ISO's) Participating Intermittent Renewables Program (PIRP). The IAP team requested both four-hour-ahead forecasts and next-day forecasts, as these time horizons are important for grid management activities. Four-hour-ahead forecasts are defined as the predicted generation from 2.75 hours to 3.75 hours after the time of delivery of the forecast, which is 15 minutes after every hour. Day-ahead forecasts are defined to occur early in the morning and cover from midnight to midnight of the following day, in one-hour intervals.

Since mesoscale modeling is normally a key input for wind forecasts, and such a model was already employed to simulate the "actual" hourly generation, it was necessary to develop a statistical model to reproduce the error patterns and dynamic behavior of real forecasts. For each time horizon, we derived from historical eWind forecasts in the state a set of error distributions as a function of forecasted generation and previous forecast error. Following a Markov chain approach, the statistical model stepped through time, drawing randomly from the error distributions to construct a realistic forecast based on the simulated generation. Finally, a bias correction was applied to eliminate a tendency of the forecasts to underestimate average generation. The results were then validated against actual forecasts to ensure they captured the correct dynamic behavior and error distribution as a function of plant output.

2.4. One-Minute Plant Output

In the final step, AWS Truewind simulated one-minute plant output data for a number of multi-hour periods for each of the sites. The time periods, which are listed in Table 1, were specified by GE Consulting.

To produce the data, AWS Truewind employed a computer program to sample four-hour windows of historical one-minute data from an existing wind project in the Midwest.[5] (No one-minute data were available from projects in California.) The program removed the 1-hour trends from each sample and added the residuals to the simulated hourly output for each site. The program did not allow the same window of residuals to be applied to two different sites in the same time period, as this would result in a perfect

[5] Wan, Yih-huei (National Wind Technology Center) and Bucaneg, Demy (Enron Wind). 2002. *Short-Term Power Fluctuations of Large Wind Power Plants.* National Renewable Energy Laboratory. NREL/CP-500-30747. Data provided to AWS Truewind by Yih-huei Wan.

correlation in the one-minute fluctuations between sites, whereas the actual correlation on this time frame is virtually zero.

3.0 Results

3.1. Site Selection

Table 2 lists the number of sites and total rated capacity selected in each region shown on the map in Figure 1.

No sites were chosen in Shasta and Vallecita (Regions 2 and 12) because the California wind resource map indicates that they have little land with an attractive wind resource. Similarly, no expansion beyond existing capacity is anticipated in Pacheco Pass (Region 6). At the other end of the spectrum, by far the largest addition, over 8000 MW, is expected in the Tehachapi wind resource area (Region 8), which includes not just Tehachapi Pass but Cottonwood Pass and other potentially attractive sites. Furthermore,

Table 1. Combined rated capacity in megawatts of sites chosen for each scenario.

Region Number	Region Name	Total Number of Sites	Existing Capacity (MW)	New 2010 Scenario (MW)	New 2020 Scenario (MW)	Total Capacity (MW)
1	Warner	10	0	0	1049	1049
2	Shasta	1	0	0	0	0
3	Montezuma	23	210	165	2517	2892
4	Solano	3	0	0	305	305
5	Altamont	26	656	80	0	736
6	Pacheco	1	13	0	0	13
7	Sequoia	4	0	0	433	433
8	Tehachapi	73	760	3555	3720	8035
9	Western Mojave	34	0	0	3810	3810
10	Eastern Mojave	19	0	0	1994	1994
11	San Gorgonio	28	463	2002	0	2464
12	Vallecita	1	0	0	0	0
13	Jacumba	4	0	90	327	417
14	Yuma	6	0	0	634	634
Total		233	2102	5892	14788	22782

the Western and Eastern Mojave areas (Regions 9 and 10), combined, would constitute an addition of about 5800 MW.

Naturally, the sites represent widely varying wind resources. Figure 3 presents one picture of the variation, a chart of cumulative wind capacity as a function of mean wind speed (presented in reverse speed order so that the most attractive sites are on the left). The three curves on this chart show how the resource varies among the existing sites and the 2010 and 2020 sites. It is apparent that the existing sites occupy some of the best

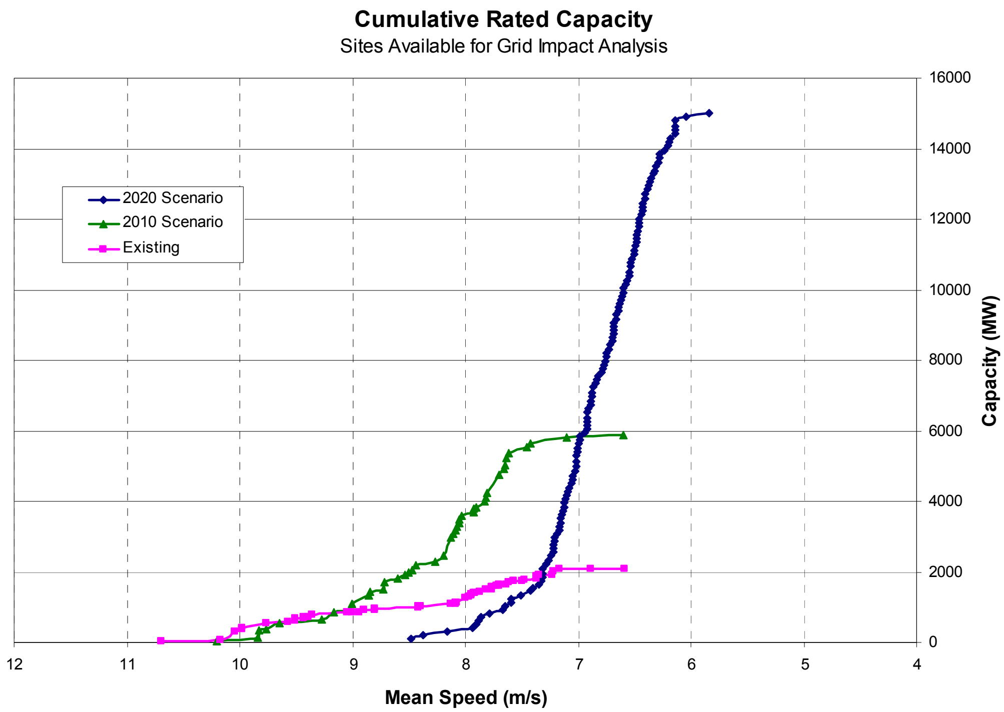


Figure 3. Chart of cumulative rated capacity for existing, 2010, and 2020 sites, as a function of mean wind speed (in reverse speed order)

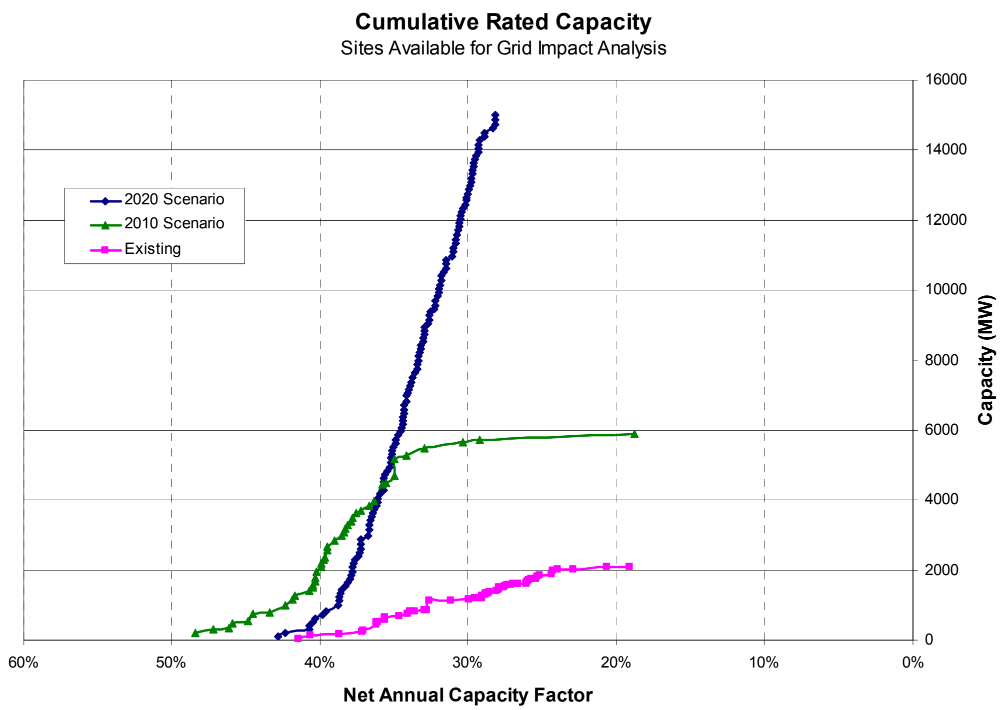


Figure 4. Chart of cumulative rated capacity for existing, 2010, and 2020 sites, as a function of net annual capacity factor (in reverse order)

wind resource areas in the state, although some of the sites in the 2010 scenario are almost equally attractive. The very large expansion of wind generation in the 2020 scenario requires developing areas of considerably lower wind speed. (However these sites provide geographic diversity, which may reduce the overall impacts on grid operations and transmission loads.)

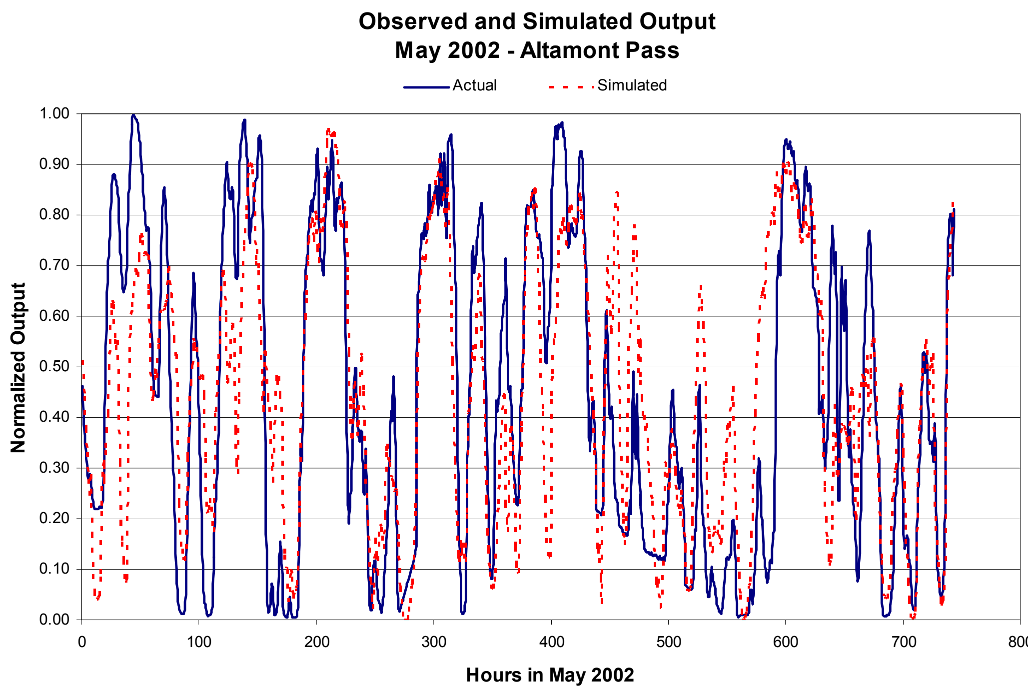
Figure 4 provides a picture of the increase in cumulative rated capacity as a function of net capacity factor. Comparing this chart with the previous makes clear that wind projects developed under the 2010 and especially 2020 scenarios will produce greater output (as a proportion of rated capacity) for the same mean speed than existing sites, a result of improvements in wind technology and the adaptation of turbines to lower-speed sites.

3.2. Hourly Wind Generation Profiles

Figure 5 presents typical examples of the simulated hourly wind generation data for one month superimposed on the actual generation for Altamont Pass and Tehachapi Pass. (The actual generation of the three main wind resource areas in 2002 was provided by the California Independent System Operator.) Although there are differences, caused most likely by limitations in the mesoscale modeling, the simulated generation tracks the actual quite well. The correlation coefficient r between the actual and simulated hourly generation for the entire year ranges from 0.79 at Altamont Pass to 0.86 at San Gorgonio Pass.

A further measure of the similarity of the actual and simulated wind generation is their dynamic behavior, which can be measured (among other ways) by the time-shifted correlation of each time series with itself (indicating the tendency of the plant output to persist from one time to the next) and by the mean absolute deviation (MAD) of output over time. Figure 6 (a) depicts the time-shifted correlation for the three wind resource areas, both simulated and actual, for 2002. The two curves for each resource area follow very similar trajectories. Figure 6 (b) shows the same for the mean absolute deviation. It is interesting that the San Gorgonio Pass wind generation tends to change by a larger amount in a given time – for example, by an average of 15% of rated capacity in six hours compared to about 13% for Tehachapi and Altamont passes. This indicates greater volatility in the San Gorgonio wind resource. The model captures this difference in dynamic behavior very well.

AWS Truewind concludes that the model accurately reproduces the dynamic behavior of the wind plant output in the main resource areas. Note that it is not expected that the simulated winds will be exactly the same as the actual at any given time. However, given that the dynamic behavior is realistic and the mean seasonal and diurnal patterns (which are adjusted to match the observed in 2002) are accurately captured, the data provide a solid basis for the grid impact simulations.



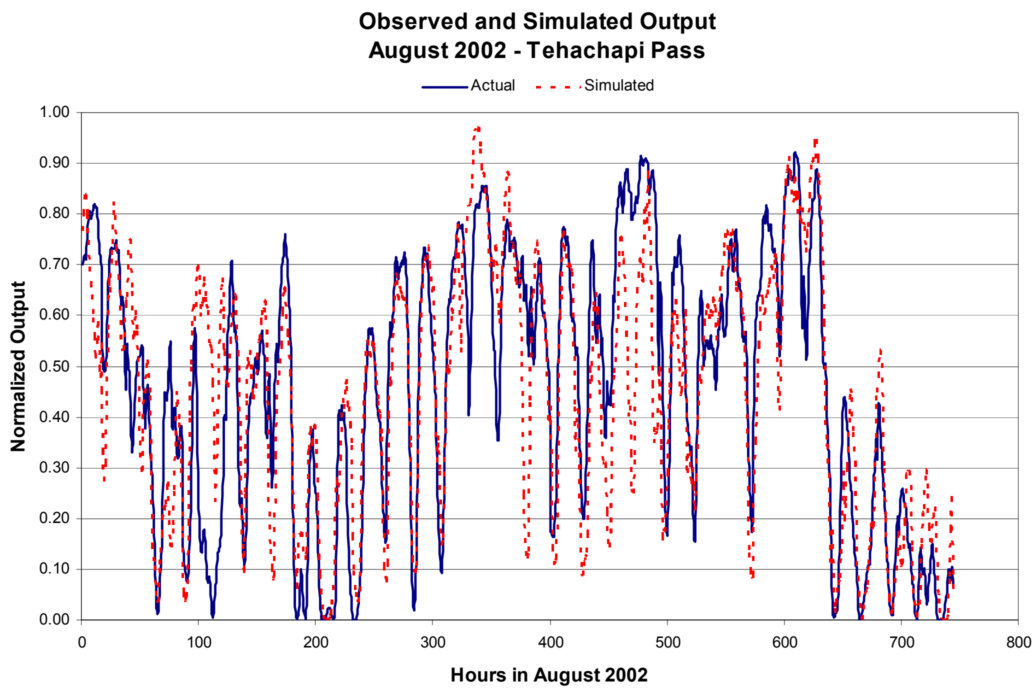


Figure 5. Comparison of actual and simulated wind generation for (a) the Altamont Pass in May 2002, and (b) the Tehachapi Pass in August 2002

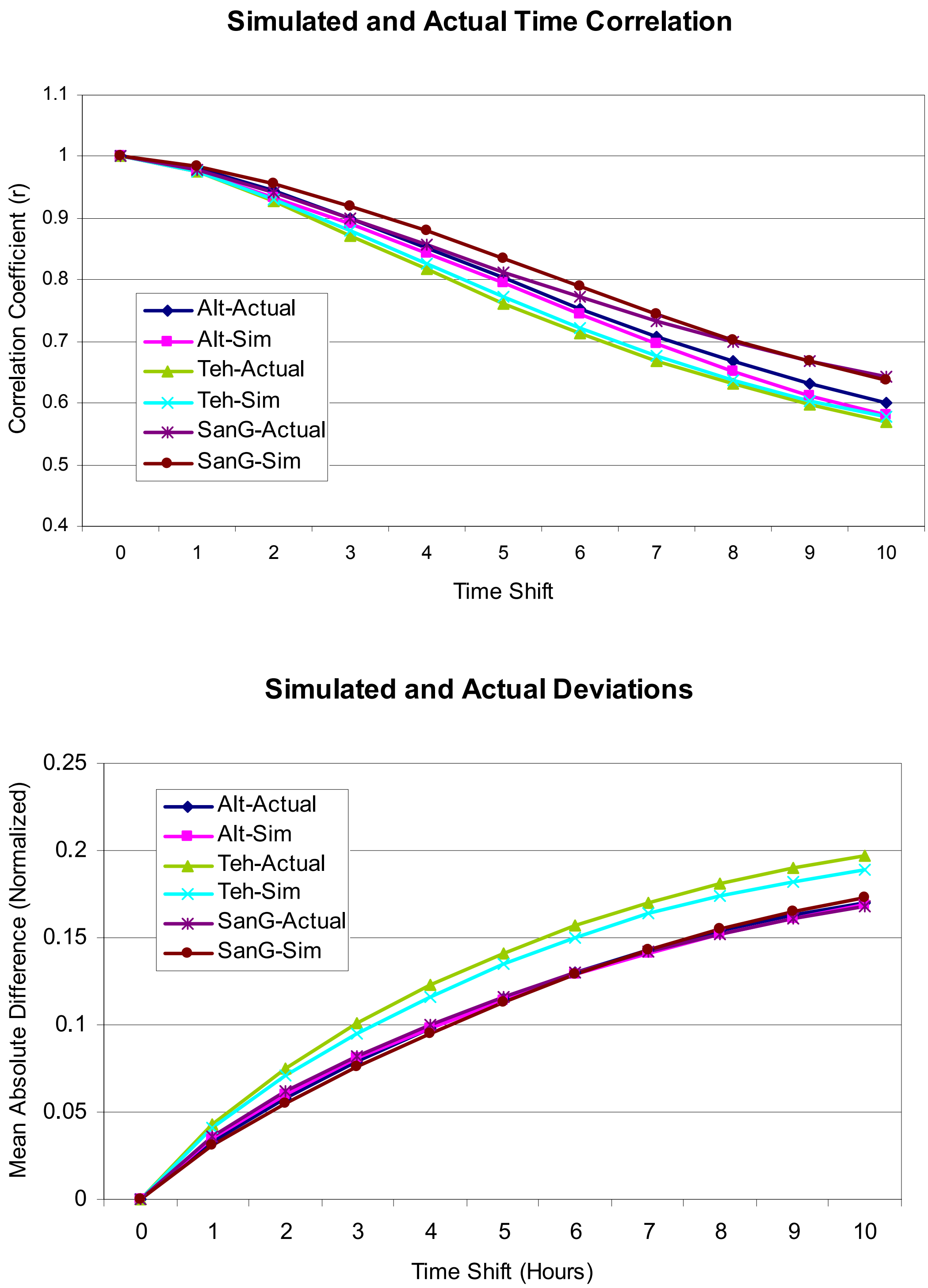


Figure 6. (a) Correlation of hourly wind generation with itself, shifted in time, for both simulated and actual generation from the Altamont (Alt), Tehachapi (Teh), and San Gorgonio (SanG) wind resource areas. (b) Same as (a) for the mean absolute difference of the normalized generation.

3.3. Forecasts

A key goal of the IAP was to produce a time series of forecasted wind generation that could be used to assess realistically the ability of forecasts to reduce the impacts of intermittent wind generation on the California grid.

Figure 7 presents an example of both next-day and four-hour forecasts for the month of June, 2003, for an existing wind project site in Tehachapi Pass. The "actual" generation in this case is that simulated by the AWS Truewind model. Although the forecasts follow the actual to a considerable degree, there are significant errors in some hours, particularly for the next-day forecasts. Such discrepancies are normal for state-of-the-art wind forecasts, since weather forecasting models do not have perfect prediction accuracy, and errors tend to grow with the forecast time horizon.

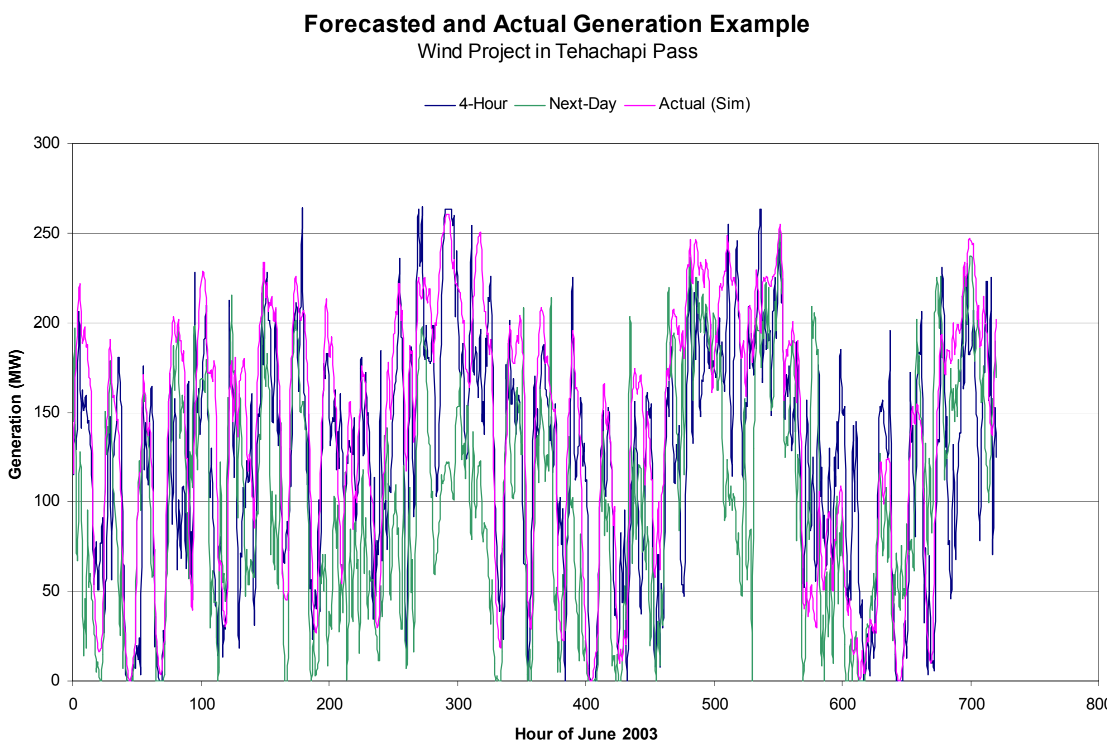


Figure 7. Typical four-hour and next-day wind forecasts for a one month period (June 2003), compared to the simulated "actual" generation, for an existing wind project in Tehachapi Pass

While the forecasts appear realistic, AWS Truewind sought to verify that their error characteristics were similar to those of actual state-of-the-art forecasts. The statistical model used to create the forecasts was based on eWind forecasts for southern California wind projects. In 2005, the mean absolute deviation (MAD) of four-hour eWind forecasts averaged 9.2% of rated capacity at both Tehachapi and San Gorgonio passes; for next-day forecasts the range was 13.1% to 16.1%. For comparison, the MAD for Tehachapi and San Gorgonio forecasts averaged 9.1% and 14.9% for four-hour and next-day forecasts, respectively. Thus, the synthesized forecasts offer similar errors to those of the actual forecasts in 2005 – as they should, since they were based on the actual error distributions.

Furthermore, the MAD of the combined four-hour forecasts is reduced to 7.4% both in the simulated and actual forecasts, while the MAD of the combined next-day forecasts is reduced to 11.4% in the simulated forecasts and 11.5% in the actual forecasts. These findings indicate that the statistical model developed by AWS Truewind accurately captures the effect of geographic diversity, which reduces the overall forecast error because random errors in different wind resource areas tend to offset each other when averaged over a large number of cases.

The accuracy of the simulated forecasts improves significantly in the 2010 and 2020 scenarios, as shown in Table 3. There are two main reasons for this improvement. First, the future scenarios (and especially the 2020 scenario) envision a much larger amount of wind capacity distributed among several new wind resource areas. This increased geographic diversity reduces the overall error rate for the reason stated above. Second, wind projects in the future are expected to have a higher average net capacity factor than existing projects, and a higher net capacity factor is typically associated with lower proportional forecasting errors.

Table 2. Error rates of the simulated forecast data.

	Four-Hour Forecasts			Next-Day Forecasts		
Region	Existing	2010	2020	Existing	2010	2020
Tehachapi	9.4%	7.8%	7.5%	14.6%	12.2%	11.5%
San Gorgonio	8.9%	8.6%	NA	14.9%	14.6%	NA
Altamont	7.3%	8.1%	NA	11.3%	12.0%	NA
All	5.5%	6.3%	4.3%	8.7%	10.3%	6.5%

It should be noted that AWS Truewind did not attempt to account for potential improvements in wind forecasting technology. Significant improvements are possible, particularly with the advent of new remote sensing platforms (including satellites) that can provide more precise and high-resolution weather data for forecasting models.

3.4. One-Minute Plant Output

Figure 8 presents a typical one-minute sample of plant output data for a single project in San Gorgonio Pass. The sample shows the wide deviations that can occur within an hour due to the passage of weather fronts and turbulent fluctuations in wind speed. The changes are consistent with data obtained from wind projects in Minnesota and Iowa. No independent validation of the one-minute deviations was possible, since AWS Truewind was unable to acquire one-minute-resolution data from any California wind projects.

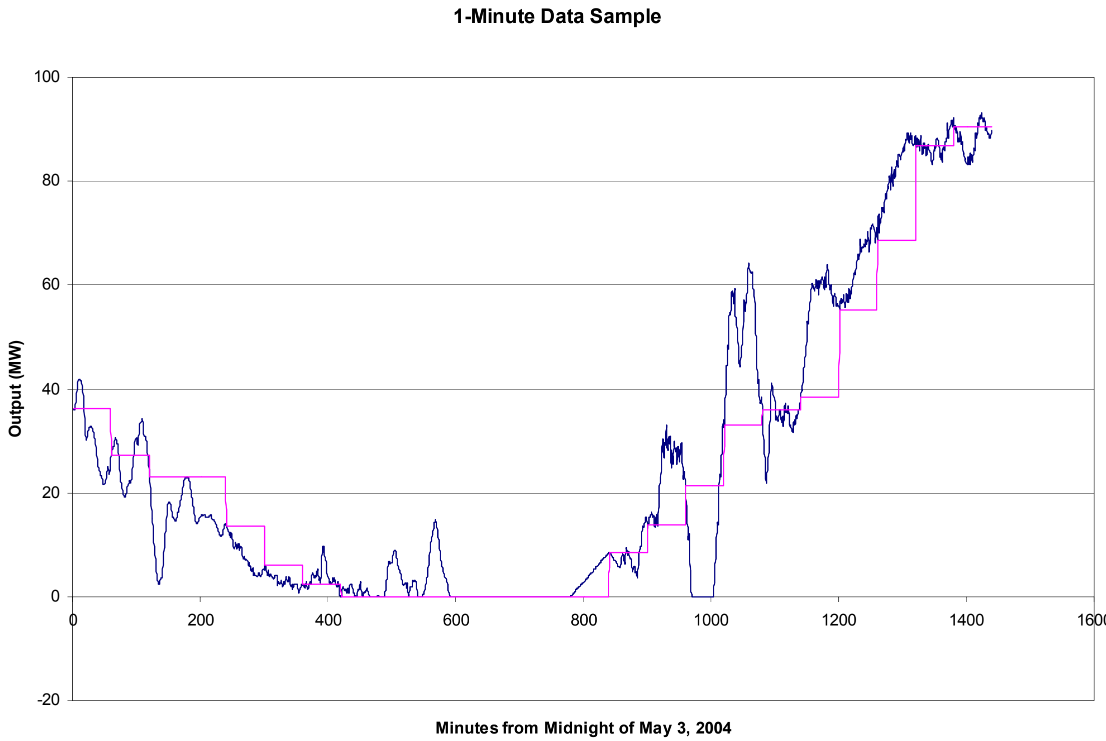


Figure 8. Sample of one-minute data for a single wind project site, overlaid on the corresponding one-hour data, for midnight to midnight on May 3, 2004

4.0 Conclusions

AWS Truewind has produced wind output and forecast data spanning three historical years and encompassing over 22 GW of existing and potential wind plant capacity. The data provide a realistic picture of future patterns of wind generation in the state, both on a one-hour and one-minute time scale, as well as a realistic picture of error patterns of state-of-the-art, four-hour-ahead and next-day wind forecasts. The data represent a critical input to the grid-impacts analyses conducted by GE Consulting for the IAP.