Energy Research and Development Division

FINAL PROJECT REPORT

ADVANCED CHARACTERIZATION OF WIND RESOURCES IN SELECTED FOCUS AREAS OF CALIFORNIA

Prepared for: California Energy Commission

Prepared by: AWS Truepower, LLC

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PREFACE

The California Energy Commission Energy Research and Development Division 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.

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Advanced Characterization of Wind Resources in Selected Areas of California is the final report for the Wind Resources project (contract number 500-06-024) conducted by AWS Truepower, LLC. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

This report presents the results of a wind measurement and mapping study to improve the understanding and predictability of wind regimes within some of California's attractive wind development regions. Wind measurements using meteorological towers and sonic detection and ranging systems were taken during a one-year period to better characterize the wind regimes of the Tehachapi Pass and Imperial Valley areas of Southern California. The results defined the wind's mean and temporal characteristics, its vertical structure, and the nature and frequency of extreme weather events. The data were also used to verify and update prior wind map predictions for wind resource in the same areas. Typical meteorological year time-series datasets were developed for nine selected state communities where net metering or load matching evaluations were important. These data sets were intended to support various community-scale wind applications.

Keywords: California Energy Commission, Tehachapi Pass, Imperial Valley, sodar, wind measurements, meteorology, AWS Truepower

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EXECUTIVE SUMMARY

Introduction

Previous efforts by the California Energy Commission have determined that publicly available data from strategically sited tall meteorological towers and sonic detection and ranging (solar) technology in promising development areas of the state can significantly improve the understanding and predictability of wind regimes. Advancements in the knowledge of attractive wind resource areas can lower the barrier of resource uncertainty that impairs the pace of development for new wind power plants as well as distribution-scale projects.

Project Purpose

This goal of this project was to expand the understanding of California's complex wind regimes in underdeveloped and undeveloped areas using a similar measurement approach combined with an improvement to the state's wind resource map.

Project Results

The project team selected two focus areas within California, Tehachapi Pass in Kern County and the Imperial Valley region in Imperial County. Both of these areas had significant wind development or expansion potential but a greater understanding was needed of the specific wind resource. New wind data was collected over a one-year period (October 2007 – September 2008) within the selected focus areas using 50 meter (m) meteorological towers and a shared sodar system. Collaboration with two wind developers, Horizon Wind Energy and Iberdrol, was instrumental in identifying high-quality wind data sources at representative locations within the focus areas. Wind data was also compiled and summarized from two other sites that had been previously assessed by another Energy Commission contractor: the Kettleman Hills site in King and Fresno Counties in central California and the Snowstorm Mountain site in Lassen County in Northern California.

The quality of the wind regimes was characterized for wind energy development within the selected focus areas, including the wind's temporal characteristics, its vertical structure, and the nature and frequency of extreme meteorological events such as extreme speeds and wind ramps, where there are big shifts in wind speed over short periods of time. The results of the new focus area wind datasets were used to verify and update prior wind map predictions of the wind resource in the same areas. The project team then developed representative time-series datasets to promote planned distributed wind energy assessment studies for nine selected state communities. As opposed to large-scale wind farms, community-scale wind systems are less likely to invest in upfront wind resource measurements, thereby placing greater importance on map-based resource projections. Time-of-day wind information could be useful because it can make assessing community-scale wind applications easier where net metering or load matching evaluations are important.

The research team recommended that additional steps be considered to incrementally improve the understanding of wind regimes in key development areas of California to build on the Energy Commission's previous efforts. Accurate wind resource assessment is a requirement for the siting and planning of wind projects and is important to several stakeholder groups, including wind project developers and owners, operations and maintenance providers, turbine manufacturers, and transmission system operators.

In addition to project siting, wind resource characteristics also have a direct and indirect bearing on project performance and safety, equipment reliability, economic feasibility, and transmission grid stability. Improved resource assessment techniques can accelerate the site characterization process at lower risk, including the use of remote sensing technologies likes sodar and the employment of advanced wind modeling and mapping techniques.

Project Benefits

This project was designed to achieve several benefits for California. Recognizing that the economic feasibility of wind energy projects is highly sensitive to the quality of the wind resource, this project provided new publically available data and map products in areas where wind development potential is high and where wind resources are predicted to be strong. Confirming the nature of the wind regimes in these areas will provide needed confidence and data to enable development activities to proceed at lower risk. This project should also help improve the long-term cost, value, environmental quality, and safety/security of the state's electricity by promoting future wind development in California.

CHAPTER 1: Introduction

In a previous project (Contract #500-03-006) for the California Energy Commission (Energy Commission), AWS Truepower (AWST; formerly AWS Truewind) measured new wind characteristics data from eleven selected locations in the northern, central, and southern portions of the State. The objective of that effort was to improve the accuracy of wind resource estimates in promising wind development areas of California. Tall towers and sodar technology were employed to better understand the nature of the atmospheric boundary layer in which modern megawatt scale wind turbines operate. The data collection effort was used to advance boundary layer numerical modeling research and to enhance the spatial resolution of the State's existing wind map within five focus areas (the original state wind map was produced by AWST as part of contract #500-01-009). The project found that new measurement locations and approaches can significantly improve the understanding and predictability of wind regimes in areas of California that are underdeveloped or undeveloped in terms of wind-based electric generation. Given that other promising development areas of the State have not yet been similarly characterized, that project recommended that additional tower and sodar measurements be taken to provide the State with better project planning capabilities.

While wind farm development will continue to be the largest of new wind-based generation and will be the largest beneficiary of any new or expanded wind measurement program, wind data applicable to the siting and planning of distribution-scale (community) wind generation is important as well. Time-of-use data in particular are desired to assess the potential revenues of net-metered wind systems.

The main objective of this project was to expand the understanding of California's complex wind regimes in underdeveloped and undeveloped areas of the State, thereby mitigating the barrier of resource uncertainty that impairs the pace of development for new wind power plants as well as distribution-scale projects. This was accomplished by:

- Selecting two focus areas within California having significant wind development or expansion potential, the Tehachapi Pass and the Imperial Valley region, where greater understanding of the wind resource is desired.
- Collecting new wind data over a one-year period within the selected focus areas.
- Obtaining wind data from other existing measurement sites in the state, thereby expanding the database of information available to define siting opportunities.
- Characterizing the quality of the wind regimes, including unusual meteorological events, within the selected focus areas for wind energy development.

Applying the results of the new wind datasets to verify and update prior wind map predictions of the wind resource in the focus areas developing representative time-series datasets to facilitate planned distributed wind energy assessment studies for some of the State's communities and utility load centers.

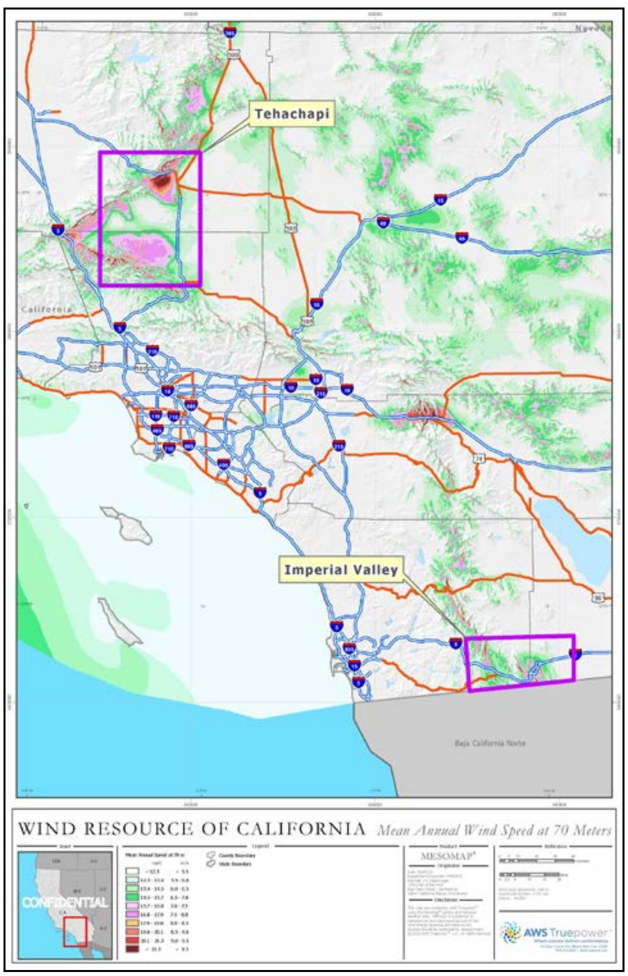
This report presents the approaches used to achieve these objectives as well as the corresponding findings and recommendations. Chapter 2 describes the siting process to identify representative measurement locations within the two selected focus areas, and Chapter 3 details the new wind monitoring campaigns that were implemented at the identified sites. The results of the measurement campaigns led to the modification of the state wind map, which is discussed in Chapter 4. The measurements were also analyzed for the presence of unusual meteorological events relevant to wind energy projects; the findings are presented in Chapter 5. Chapter 6 describes the process used to create annual time-of-use wind statistics for several locales throughout the state where distributed wind applications are under consideration. Conclusions and recommendations from this project are summarized in Chapter 7.

This project was designed to achieve a number of benefits to California. Recognizing that the economic feasibility of wind energy projects is highly sensitive to the quality of the wind resource, this project provides new publically available data and map products in areas where wind development potential is high and where wind resources are predicted to be strong. Confirmation of the nature of the wind regimes in these areas will provide needed confidence and data to enable development activities to proceed at lower risk. By facilitating future wind development in the State, this project should also help improve the long-term cost, value, environmental quality, and safety/security of the State’s electricity.

CHAPTER 2: Site Selection

At the outset of this project, the Tehachapi Pass and Imperial Valley regions of southern California were determined by the Energy Commission to be the two focus areas of interest for this study. The locations of the two selected focus areas are shown in Figure 1. Tehachapi Pass, which lies within Kern County to the west of the community of Mojave, has experienced significant wind development over the past 25 years and contains more development opportunities, especially if proposed transmission upgrades within the area are implemented. The area also contains many first generation wind technologies that are being replaced (repowered) with current generation turbines. The Imperial Valley area lies within eastern San Diego County and western Imperial County and is bordered by Mexico to the south. There is only one operating wind farm within this focus area.

Figure 1: Focus Areas: Tehachapi Pass and Imperial Valley



Source: AWS Truepower

The goal of the site selection portion of this project was to identify candidate wind measurement opportunities and to ultimately select one representative site within each focus area. A screening process was first employed to identify existing tall meteorological towers operated by wind farm developers who would be willing to publicly share the wind data. If viable options were not identified in one or both focus areas, then options for installing new wind measurements would be identified. It turns out that this second step was not necessary.

The screening process for identifying existing meteorological (met) towers was guided by a set of criteria to meet the needs of this study:

- Minimum tower height of 50 m with at least two measurement levels
- Located at a site that is representative of the area's developable wind conditions
- Availability of an adjacent site for a 3-month sodar campaign
- Measurement period inclusive of the fall 2007 to fall 2008 period
- Wind data for the target period must be releasable into the public domain

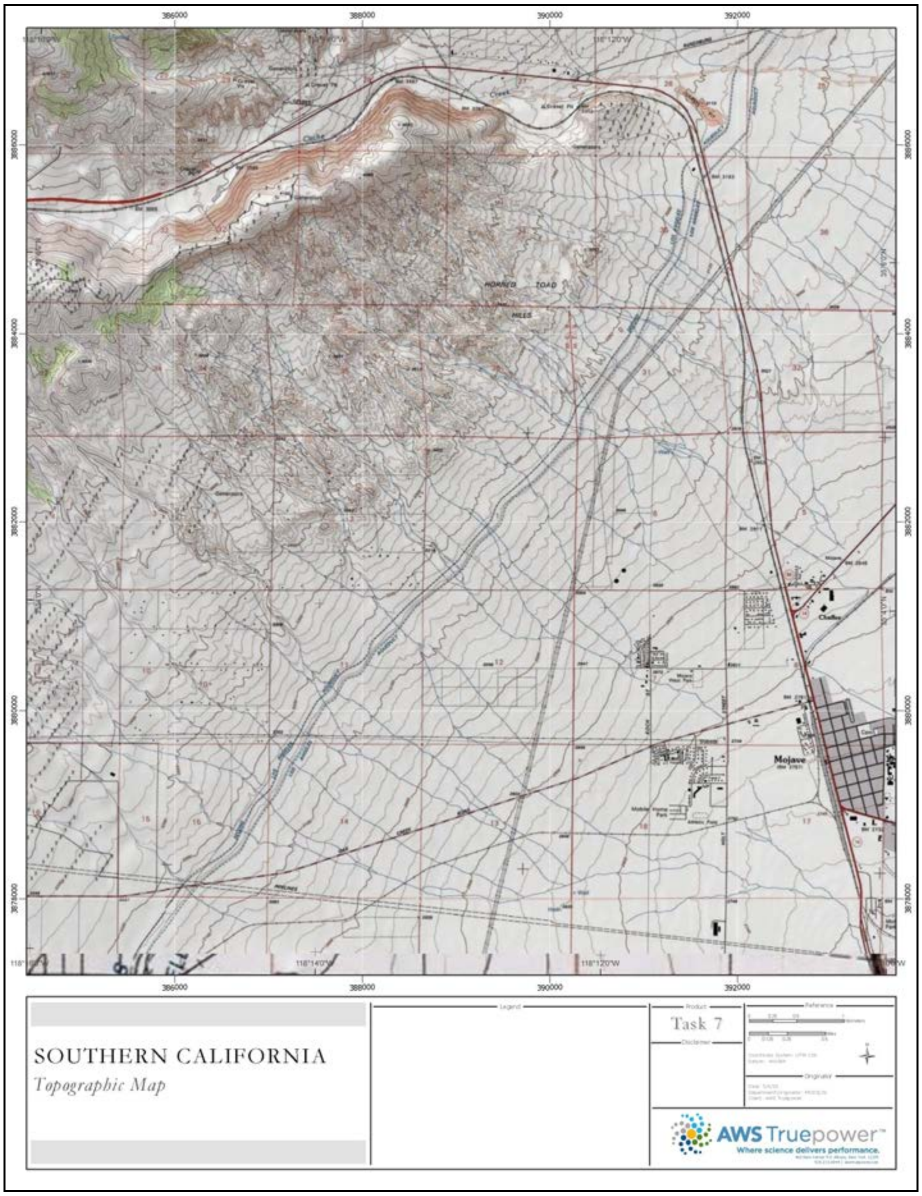
Developers were generally unwilling to have their wind data publically released, but two developers—Horizon Wind Energy and Iberdrola—were willing on the condition that the exact location of the towers was not publically disclosed. Because the goal of this study is to characterize the winds of specific focus areas and not exact sites, this condition was agreed to by formal agreement with AWST. For this reason, the exact locations of the measurement studies are not identified in this report and have not been disclosed to the Energy Commission.

Both focus areas had more than one met tower to choose from, so all of the towers, a total of 5, were visited to determine their location, accessibility and other logistics, representative quality, physical condition, and sodar assessment suitability. The following subsections give general descriptions of the selected sites.

2.1 Tehachapi Focus Area – Kern County, CA

The Tehachapi Pass is well known for its attractive wind resource, which is driven by a combination of high pressure off the Pacific Coast, differential heating between the Pacific Ocean and the Mojave Desert, and funneling of the winds through the pass from the San Joaquin Valley into the Mojave Desert. The terrain slopes downward from northwest to southeast and the area consists of barren desert with sparse low shrubs, resulting in a low surface roughness. A topographic map of the area of interest is presented in Figure 2

Figure 2: Tehachapi Pass Focus Area Monitoring Locale



Source: AWS Truepower

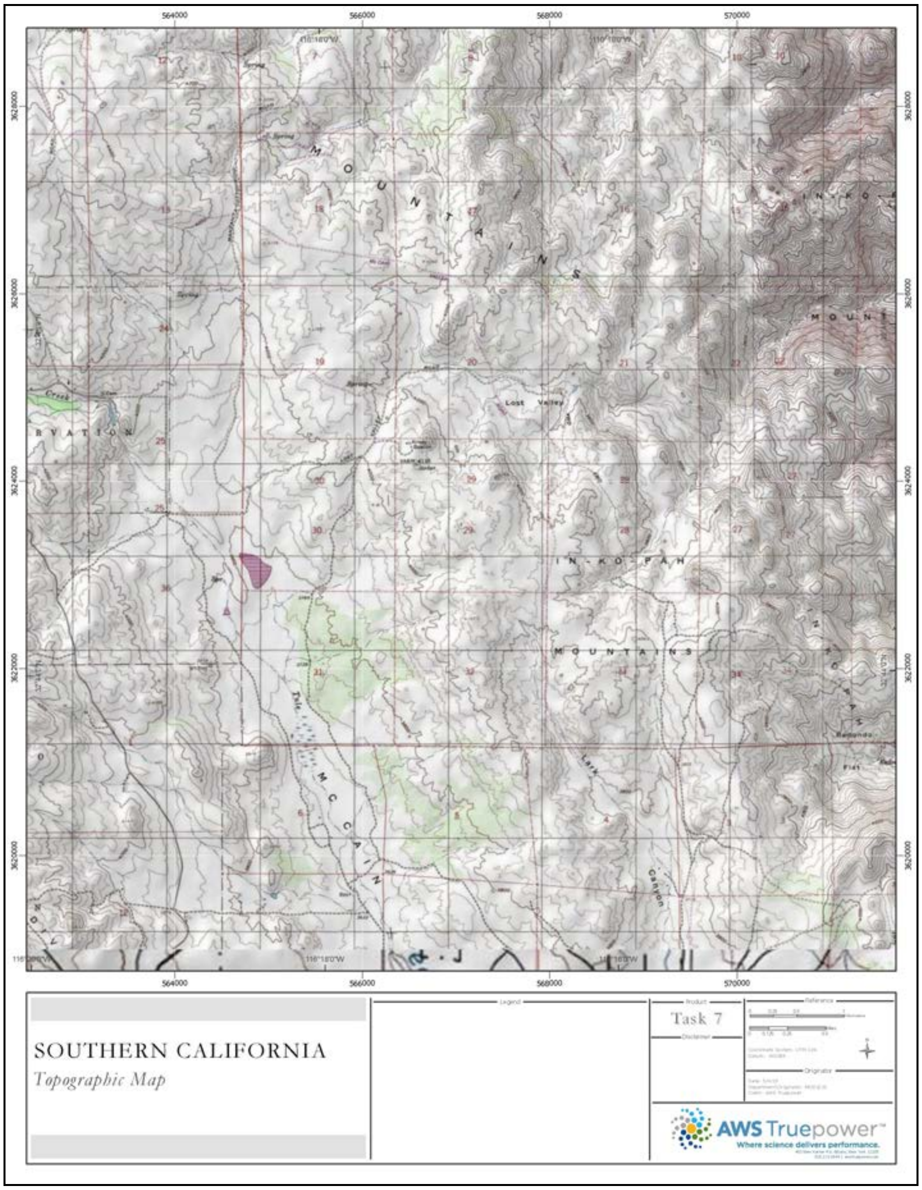
Three met tower sites within this focus area were inspected. The towers were located downwind (to the east and northeast) of a number of first generation wind farms. It was recognized that the sodar campaign could provide added value by assessing the effect of the up-wind turbine arrays on the winds aloft (for example, above the height of the met towers). The selection of one tower for this study was driven by the ease of access for transporting and siting the sodar system on flat ground within 80 m of the tower.

2.2 Imperial Valley Focus Area – San Diego County, CA

Prior wind mapping studies of the state indicate there to be an attractive wind resource on higher terrain in the immediate vicinity of the Imperial Valley. The area's terrain is complex and consists of hills and steep-sided ridges that are collectively known as the In-Ko-Pan Mountains. The locally sparse vegetation is mainly scrub brush. A topographic map of the area of interest, which is focused on the San Diego County portion, is presented in Figure 3.

Two available met towers sites in the southeast corner of San Diego County were inspected. The one determined to be most centrally positioned within the area of predicted strong wind resource was selected. Because of the ruggedness of the tower site, the closest accessible site for the sodar system was approximately 3.7 km to the southeast. This location was acceptable for the purposes of this study because it was at the same elevation as the tower and provided the opportunity to measure the spatial continuity of the local winds. Permission was granted by the Bureau of Land Management to temporarily site the sodar on the identified property, which is federally owned.

Figure 3: Imperial Valley Focus Area Monitoring Locale



Source: AWS Truepower

CHAPTER 3: Wind Measurement Campaign

This section describes the wind measurement programs at the Tehachapi Pass and Imperial Valley focus areas. The measurement programs consisted of one-years' worth of wind measurements from a meteorological tower located within each area, together with a shorter-term of several months)of overlapping data from a measurement program using a shared sodar system, which probes the lower atmosphere to significantly greater heights than the towers. While the towers served to provide a complete annual record of local wind conditions at heights of up to approximately 50 m above ground, the sodar system obtained wind data at greater heights (up to 200 m) to include the full rotor span of today's megawatt-scale wind turbines.

Both towers collected data from 01 October 2007 to 30 September 2008. The shared sodar system was first deployed in Tehachapi Pass for approximately four months beginning in February 2008, and was redeployed in the Imperial Valley for over five months beginning in May 2008. The sodar deployments were timed to ensure that significant portions of the spring-summer high wind seasons were captured at both sites.

The met tower at both sites was a 50-m guyed, tubular NRG Tall Tower that employed an NRG Symphonie logger to collect data. This tower type is widely used by the wind energy industry for conducting wind resource assessments. The specifics for the sensor orientations for each site are as follows:

- Tehachapi Pass – Wind speed was recorded at three levels (49.1 m, 29.6 m, and 10.4 m); wind direction at two levels (47.9 m and 30.5 m); and temperature at a height of 3 m. Two anemometers, one facing north and the other facing west, were present at both of the upper two levels, while a single anemometer oriented toward the west was at the lowest level.
- Imperial Valley – Wind speed was recorded at four levels (50.0 m, 49.0 m, 40.0 m, and 30.0 m); wind direction at two levels (50.0 m and 30.0 m); and temperature at a height of 2.0 m. All anemometers were mounted on horizontal booms oriented toward the west.

Both towers sampled data every 2 seconds and recorded 10-minute averages and standard deviations. Monthly data files were acquired from the tower owners and subjected to a screening and validation process that checked for data quality, consistency, and completeness. Validated monthly records were compiled into a master database. Quarterly reports, which provided statistics on the average wind speed, speed frequency distribution, wind direction rose, wind shear, turbulence intensity, and the monthly/diurnal variations in these parameters, were submitted to the Energy Commission.

The sodar system model used by this study was the Atmospheric Research & Technology (ART) VT-1; see Figure 4. Sodar (<u>so</u>nic <u>d</u>etection and <u>r</u>anging) is a ground-based remote sensing technology that emits acoustic pulses (i.e., chirps or beeps) upward into the atmosphere to measure the profile of the three-dimensional wind vector up to heights of 200 m above ground level. Receivers within the sodar system respond to echoes from the atmosphere generated by the small-scale temperature fluctuations associated with atmospheric turbulence. The echoes are shifted in frequency due to the Doppler Effect. By analyzing the timing and the frequency shift of the returned echoes, the instrument derives the profile of the horizontal wind speed and direction with 10 m vertical resolution. It also provides information on the vertical component of the wind.

The sodar system collected data samples every several seconds and recorded 10-minute values. As with the towers, the data records were screened and validated for quality, consistency and completeness. A separate sodar report was prepared and submitted that summarized the data findings and made comparisons with simultaneous measurements from the nearby met towers.

Sections 3.1 and 3.2 present the key findings for the wind measurement campaigns at both focus areas. In addition, wind data from two unrelated wind measurement programs sponsored by the Energy Commission (Contract No. 500-01-042) are summarized in Section 3.3. The data from two met towers were collected by a separate firm (DISGEN) for portions of 2005 and 2006, and the data had not been previously analyzed or reported. Therefore this study included the task of validating and summarizing the wind data from these other measurement programs.

Figure 4: ART Sodar System

Photo credit: AWS Truepower

3.1 Tehachapi Pass Focus Area

Table 1 summarizes the wind resource characteristics observed over the one-year period at the top measurement level (49.1 m) of the tower. Statistics include the annual average wind speed, shear exponent, turbulence intensity, Weibull parameters, prevailing wind direction, and air density. The data recovery over the period of record was an excellent 99.4percent.

The observed annual average wind speed was 9.02 m/s. The annualized average wind speed, which weights each calendar month according to its number of days, was essentially the same—9.01 m/s.

Table 1: Summary of Observed Wind Resource Characteristics – Tehachapi Pass

Parameter	Annual Value
Measurement Height (m)	49.1
Period of Record	1 Oct 2007 – 30 Sep 2008
Data Recovery	99.4%
Annual Average Wind Speed (m/s)	9.02
Wind Shear Exponent* (*Only wind speeds > 4 m/s used in calculation.)	0.14 (49.1 m/29.6 m)
Turbulence Intensity at 15 m/s	0.11
Weibull Parameters (A/k)	10.96 m/s / 1.40
Prevailing Wind Energy Direction	WNW
Air Density (kg/m³)	1.080

Source: AWS Truepower

The wind shear exponent, which is a common way of expressing the rate of speed change with height, was calculated using the power law equation:

$$U_2 = U_1 (Z_2/Z_1)^p$$

where

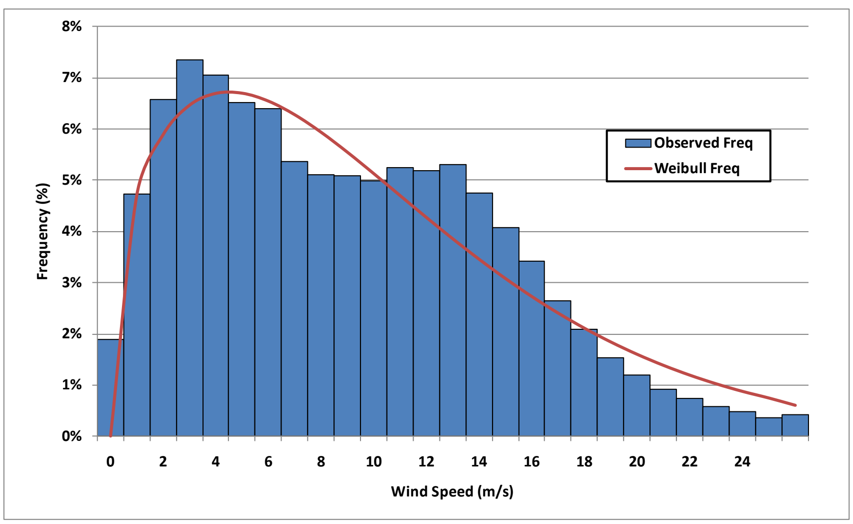
U_2 = the measured wind speed at height Z_2 above ground;
U_1 = the measured speed at height Z_1; and
p = the shear exponent.

This equation is an empirical relationship that is widely employed in the practice of wind resource assessment. The observed wind shear exponent at the tower was 0.14, which is consistent with the surrounding area's terrain and surface roughness. The shear was calculated from the mean wind speeds at the 49.1 m and 29.6 m heights. Only wind speeds greater than 4 m/s, the range of interest for energy production, were used in the calculation.

The turbulence intensity indicates short-term (2-sec) fluctuations (expressed as a standard deviation) in the wind speed recorded by the anemometer within each 10-minute interval as a function of the average interval speed. The observed turbulence intensity at 15 m/s, which is a reference speed commonly used by wind turbine manufacturers, was 0.11, which is considered low-to-moderate.

The Weibull function is an analytical curve that describes the wind speed frequency distribution or number of observations in specific wind speed ranges. Its two adjustable parameters allow a reasonably good fit to a wide range of actual distributions. *A* is a scale parameter related to the mean wind speed while *k* controls the width of the distribution. Values of *k* typically range from 1 to 3.5, the higher values indicating a narrower distribution. The observed *k* value (1.40) indicates a highly variable wind resource. Figure 5 shows the observed frequency distribution and fitted Weibull curve for the Tehachapi site.

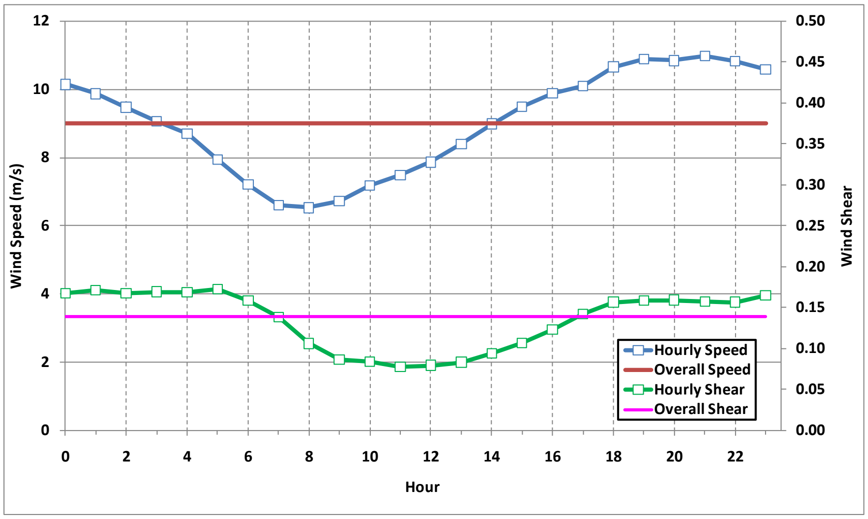
Figure 5: Tehachapi Pass Observed Wind Speed Frequency Distribution and Fitted Weibull Curve



Source: AWS Truepower

Figure 6 depicts the variation in average wind speed with time of day at the tower's top level. The average speed varies from a low of approximately 6.5 m/s at 8 am in the morning (PST) to a high of about 11.0 m/s during the evening hours. As shown on the same figure, the average wind shear exponent varies from a maximum of about 0.17 during the overnight hours to a minimum of 0.08 during late morning and early afternoon. This pattern reflects daily variations in the thermal stability of the atmosphere and the depth of the boundary layer.

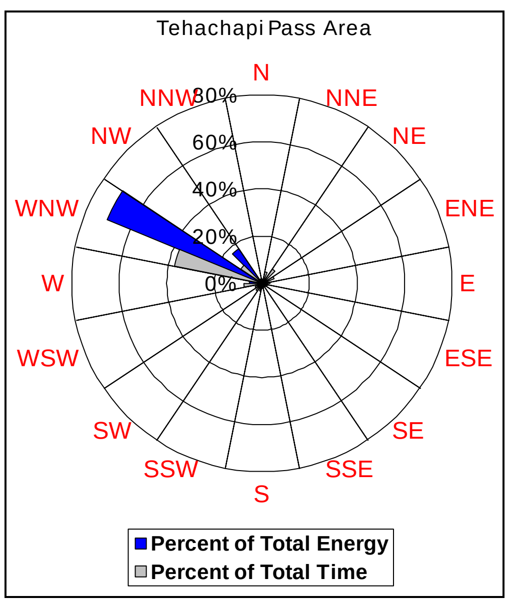
Figure 6: Tehachapi Pass 49.1 m Diurnal Wind Speed and Shear Distribution



Source: AWS Truepower

The wind frequency and energy distribution by direction at this site is plotted as a wind rose in Figure 7. The wind rose indicates that the highest concentration of energy producing winds (shown in blue) is out of the west-northwest and northwest direction sectors, comprising almost 90 percent of the total energy. Wind direction frequencies as a percent of time also showed a strong dominance from the same direction sectors, indicating that the winds at this locale are virtually unidirectional.

Figure 7: Tehachapi Pass Wind Rose



Source: AWS Truepower

The air density directly affects a wind turbine's energy production: the greater the density, the greater the power output of a turbine for the same speed distribution. The estimated air density of 1.080 kg/m³ was calculated from the following equation:

$$\rho = \frac{P_o e^{\left[-\frac{gz(1.0397-0.000025z)}{RT}\right]}}{RT}$$

where

ρ = Air density (kg/m³)
P_0 = Standard sea-level atmospheric pressure in Pascals (101325 Pa)
R = Universal gas constant (287 J/Kg·K)
T = Air temperature (ºK)
g = Acceleration due to gravity (9.8 m/sec²)
z = Elevation of temperature sensor (m)

This equation was applied to each 10-minute data record, and a weighted average was calculated for the year in which the weight was proportional to the energy content of the wind (such as the cube of the wind speed).

Table 2 lists the observed monthly average wind speeds and data recovery percentages for the site. The strongest winds occurred during the March – August period, with mean values of roughly 10.0 to 12.0 m/s at the tower's top measurement level. The weakest winds were observed during the late fall and early winter months. These seasonal trends are typical of the region. The relatively strong spring and summer winds are caused by the large continental/marine temperature and pressure gradients that develop during the warm season due to intense heating within the desert regions.

Table 2: Tehachapi Pass Monthly Mean Wind Speeds and Data Recoveries

Month-Year	49.1 m Speed (m/s)	Data Recovery (%)
Oct-07	8.13	98.8%
Nov-07	5.59	100.0%
Dec-07	6.37	100.0%
Jan-08	7.05	96.6%
Feb-08	7.14	96.0%
Mar-08	10.13	100.0%
Apr-08	10.40	100.0%
May-08	11.62	100.0%
Jun-08	12.17	100.0%
Jul-08	10.84	100.0%
Aug-08	10.75	100.0%
Sep-08	7.76	100.0%
Average Speed	**9.02**	**99.4%**

Source: AWS Truepower

The long-term mean wind speed at the Tehachapi tower was estimated using the Measure-Correlate-Predict (MCP) technique. A linear regression equation was established between concurrent daily mean wind speeds at the tower and the National Weather Service Automated Surface Observing System (ASOS) surface station at Lancaster, California. This yielded a long-term 49.1-m mean wind speed of 8.68 m/s, which is about 3.8 percent lower than what was measured for the one-year period. Using the observed shear exponent of 0.14, the resulting 80-m long-term mean wind speed is estimated to be 9.29 m/s. Table 3 contains a summary of the long-term and hub height wind speed projections.

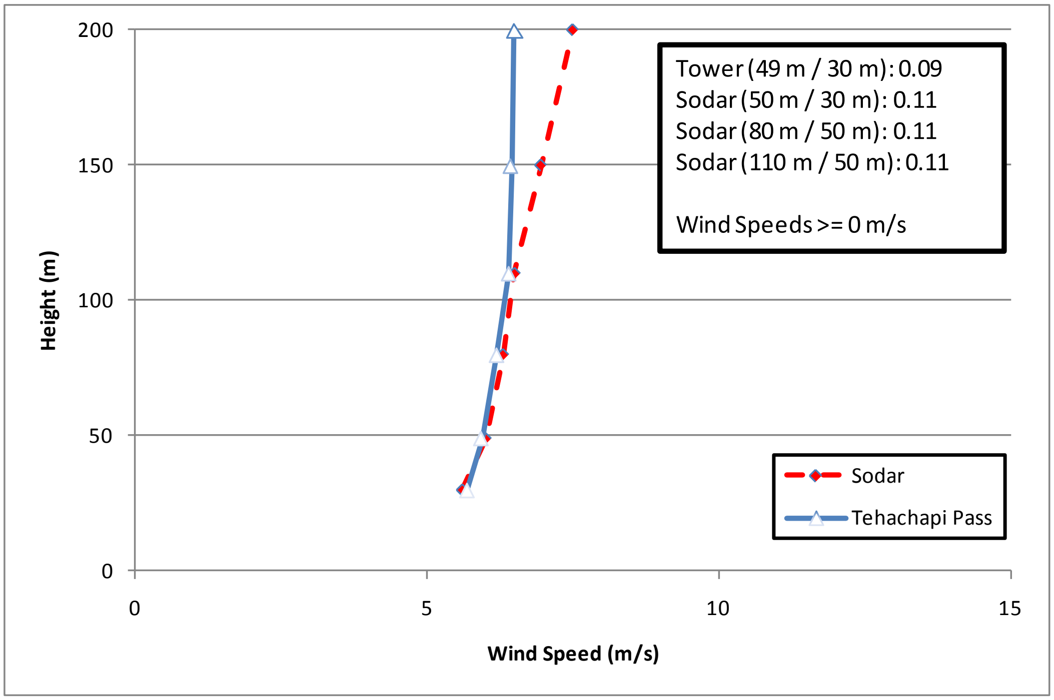
Table 3: Tehachapi Pass Climate-Adjusted 80 m Hub Height Wind Speed Projection

Tower	Monitoring Height (m)	Observed Annual Average Speed (m/s)	Reference Station	Climate-Adjusted Speed (m/s)	Wind Shear Exponent	Projected 80-m Long-Term Wind Speed (m/s)
Tehachapi	49.1	9.02	Lancaster, CA	8.68	0.14	9.29

Source: AWS Truepower

The sodar system was located roughly 77 m to the northwest of the tower and collected vertical profile data 12 February 2008 to 7 May 2008; data recovery was 93 percent. During this period, average wind speeds and directions near the 50 m level were in excellent agreement (±2 percent and ±5 degrees, respectively). The mean wind shear profile as measured by the sodar is shown in Figure 8 for all wind speeds; also shown is the extrapolated profile from the tower. During this period, the sodar verified that the wind shear profile at above the tower at heights of up to 110 m is consistent with that measured by the tower (30 – 50 m). During windier conditions (>4 m/s), the sodar profile is consistent with the tower's extrapolated profile up to even greater heights, and shared the same average shear exponent value of 0.14.

Figure 8: Tehachapi Pass Sodar and Tower Wind Speed Profiles



Source: AWS Truepower

3.2 Imperial Valley Focus Area

Table 4 summarizes the wind resource characteristics observed over the period of record, including the observed mean wind speed, shear exponent, turbulence intensity, Weibull parameters, and air density. The data recovery for the period of record was a high 99.4 percent.

Table 4: Imperial Valley Tower Summary of Observed Wind Resource Characteristics

Parameter	Annual Value
Measurement Height (m)	50.0
Period of Record	1 Oct 2007 – 30 Sep 2008
Data Recovery	99.4 percent
Observed Mean Wind Speed (m/s)	7.21
Wind Shear Exponent* (*Only wind speeds > 4 m/s used in calculation.)	0.09 (50 m/30 m)
Turbulence Intensity at 15 m/s	0.09
Weibull Parameters (A/k)	7.55 m/s / 1.86
Prevailing Wind Energy Direction	WSW
Air Density (kg/m^3)	1.073

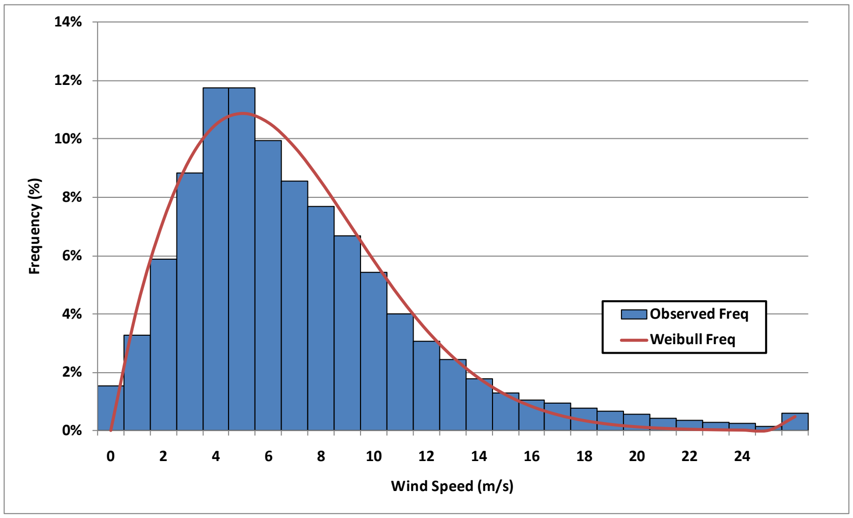
Source: AWS Truepower

The measured annual average wind speed at 50 m was 7.21 m/s, while the annualized mean wind speed, which weights months by their number of days, was 7.20 m/s. The observed 50 m turbulence intensity at the reference speed of 15 m/s was 0.09, which is considered low. The annual average air density was 1.073 kg/m^3.

The observed shear exponent, which was calculated from the mean speeds at the 50 m and 30 m levels of the tower, was 0.09. This value is consistent with the tower location and the surface roughness.

Figure 9 shows the observed speed frequency distribution and fitted Weibull curve for the site. The observed *k* value, 1.86, indicates a varying wind resource with occasional high wind events.

Figure 9: Imperial Valley Observed Wind Speed Frequency Distribution and Fitted Weibull Curve

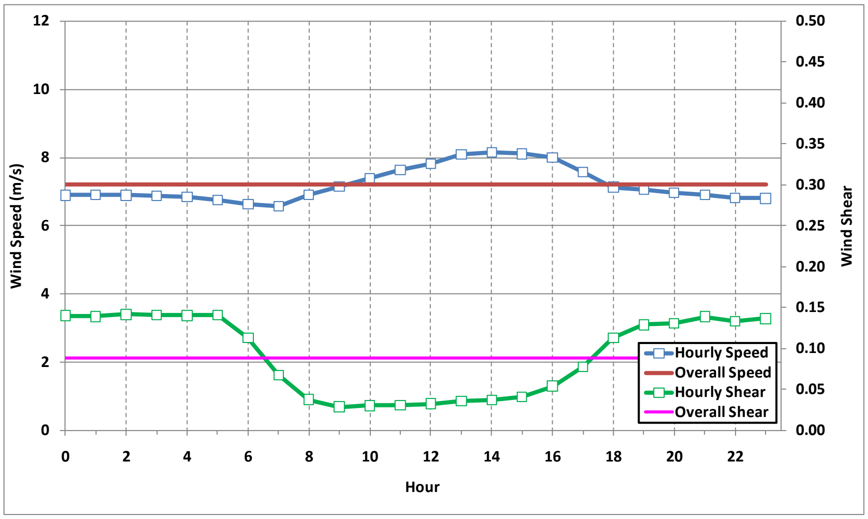


Source: AWS Truepower

Figure 10 depicts the variation in average wind speed with time of day. The average speed at 50 m reached a maximum during the early and mid-afternoon and diminished during the late afternoon and evening, reaching a minimum at mid-morning. The average wind shear exponent varied from a maximum of about 0.14 during the evening and early morning hours to a minimum of about 0.03 during the mid-morning to mid-afternoon period. This pattern reflects daily variations in the thermal stability of the atmosphere and depth of the boundary layer.

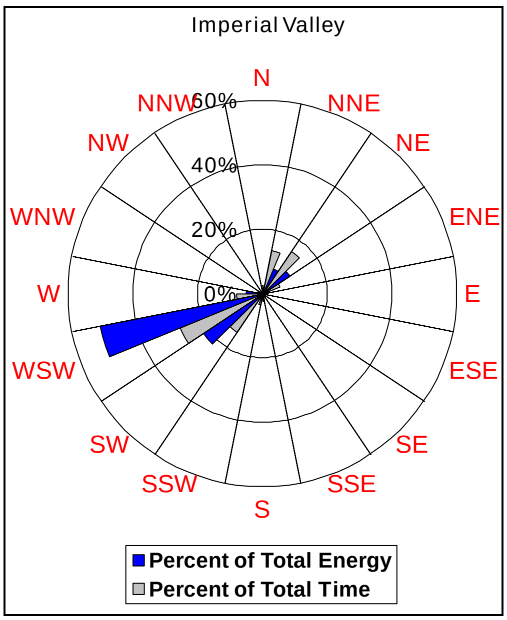
The wind frequency and energy distribution by direction is plotted in Figure 11. The wind rose indicates that the highest concentration of energy producing winds is out of the west-southwest and southwest direction sectors, comprising almost 75 percent of the total energy. This focus area lies within the zone of prevailing westerlies and is on the east side of the semi-permanent high pressure area of the northeast Pacific Ocean. This causes a prevailing westerly wind flow over the valley for most of the year.

Figure 10: Imperial Valley 50 m Diurnal Wind Speed and Shear Distribution



Source: AWS Truepower

Figure 11: Imperial Valley Wind Rose



Source: AWS Truepower

The observed monthly wind speeds and data recovery percentages for the Imperial Valley tower are presented in Table 5. The highest mean speeds were observed during the winter and spring months, while the lighter winds were occurred throughout the summer months. This trend differs from the Tehachapi Pass focus area in that the seasonal maximum and minimum winds occur about two months sooner in the Imperial Valley. This trait is attributable to the lower latitude and different geography of the Imperial Valley.

Table 5: Imperial Valley Monthly Mean Wind Speeds and Data Recoveries

Month-Year	50 m Speed (m/s)	Data Recovery (%)
Oct-07	8.47	100.0%
Nov-07	5.90	100.0%
Dec-07	7.94	98.5%
Jan-08	9.46	100.0%
Feb-08	8.09	97.7%
Mar-08	8.01	100.0%
Apr-08	9.29	100.0%
May-08	8.31	98.9%
Jun-08	7.12	100.0%
Jul-08	5.33	100.0%
Aug-08	3.67	97.7%
Sep-08	4.89	100.0%
Average Speed	**7.21**	**99.4%**

Source: AWS Truepower

Because a high quality surface reference station was not available for this locale, the long-term mean wind speed at the tower was estimated using a linear regression between concurrent daily mean wind speeds at the tower and a model-based climate data set developed by AWST, which is referred to as the windTrends database. This database is a 13-year simulated hourly time series, beginning in 1997, of numerical weather prediction model output covering the conterminous United States and southern Canada. It is essentially a controlled regional reanalysis dataset that is more precise than the conventional reanalysis data generated by the U.S. government because it is computed at a finer resolution (20 km) and relies on fixed observational data (rawinsonde).[1] For this analysis, the model output was interpolated to the exact location of the met tower. This yielded a long-term 50-m wind speed of 7.11 m/s at the Imperial Valley site, which is 1.4 percent lower than the observed one-year average speed. Using the one-year observed shear of 0.09, the resulting 80-m long-term mean wind speed becomes 7.42 m/s. Table 6 provides a summary of the long-term and hub height wind speed projections.

[1] Taylor, Mark, et al., "Using Simulated Wind Data from a Mesoscale Model in MCP", Proceedings of WindPower 2009, May 2009.

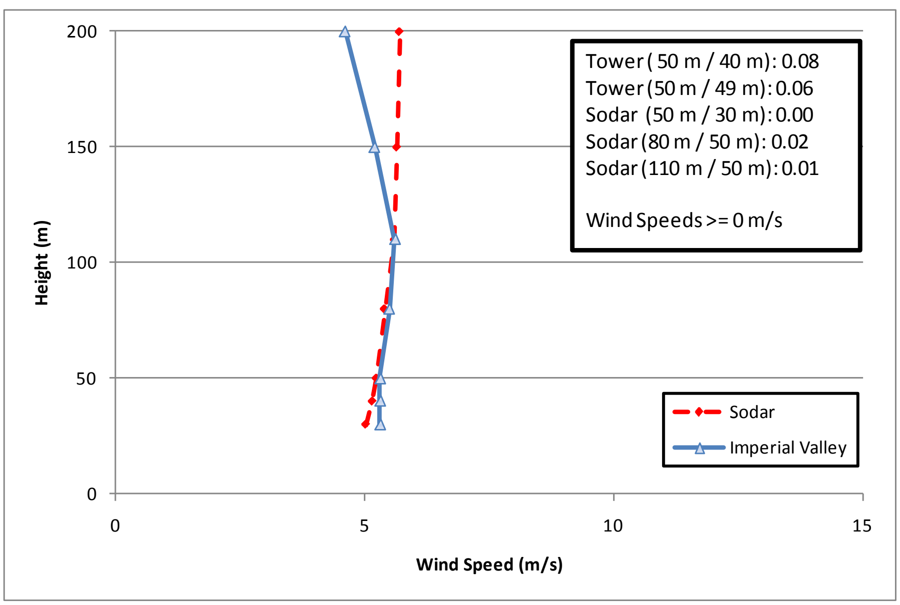
Table 6: Imperial Valley Climate-Adjusted 80 m Hub Height Wind Speed Projection

Tower	Monitoring Height (m)	Observed Annual Average Speed (m/s)	Reference Station	Climate-Adjusted Speed (m/s)	Wind Shear Exponent	Projected 80-m Long-Term Wind Speed (m/s)
Imperial Valley	50	7.21	*windTrends*	7.11	0.09	7.42

Source: AWS Truepower

The sodar system was located approximately 3.7 km to the southeast of the tower and collected vertical profile data from 9 May 2008 to 30 September 2008; data recovery was 81 percent. Placement of the sodar unit at this distance from the tower was necessitated by terrain ruggedness and land availability limitations. Despite the spatial separation, average wind speeds and directions near the 50 m level during the concurrent measurement period were in excellent agreement (±2 percent and ±5 degrees, respectively). The mean wind shear profile as measured by the sodar is shown in Figure 12; also shown are the observed speeds at the tower levels and the extrapolated profile above the tower using the observed tower shear. During this period, the shear observed by the sodar was close to zero, meaning that speeds were essentially constant with height up to a level of 110 m or so above the ground. Average speeds gradually decreased above that level. The difference in shear between the two locations arose because of terrain, as the sodar was located on a small steep-sided hill such that prevailing winds were flowing downhill (mean angle of -1.4° to -2.4° from horizontal). This type of flow often results in low, even negative, shear.

Figure 12: Imperial Valley Sodar and Tower Wind Speed Profiles

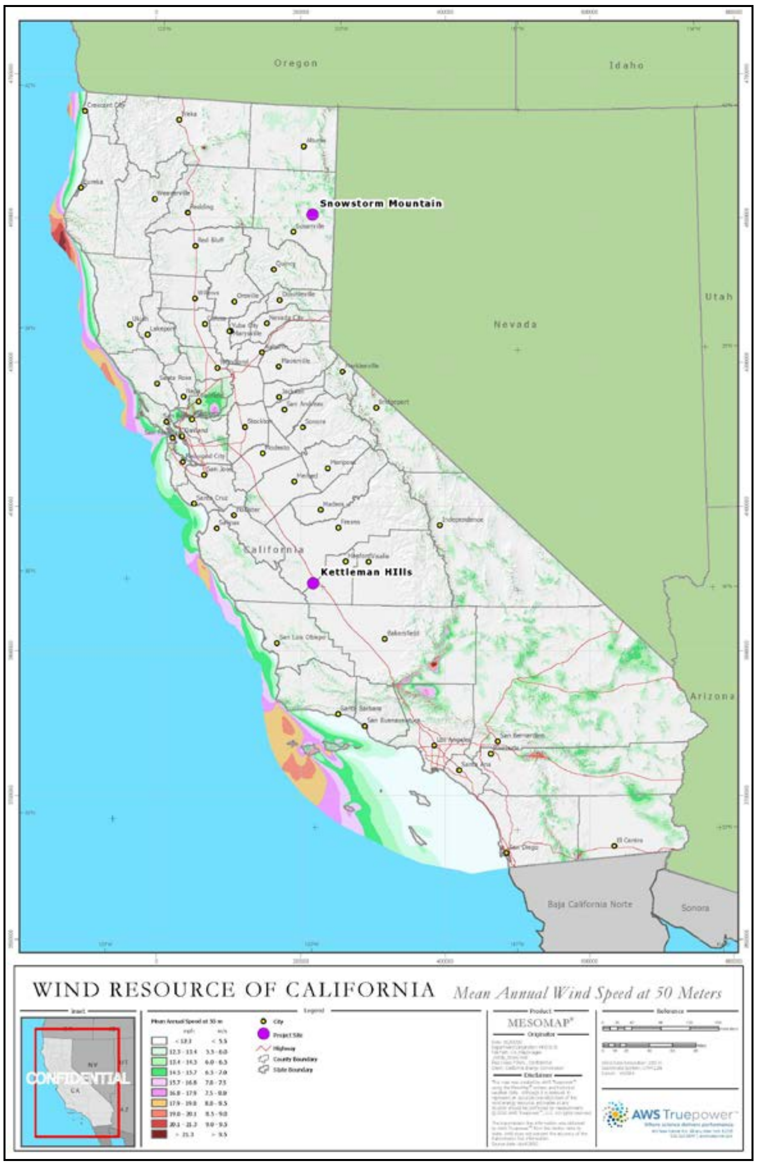


Source: AWS Truepower

3.3 Kettleman Hills and Snowstorm Mountain

As a supplemental task of this project, wind data were acquired from the firm DISGEN for two sites in central and northern California—Kettleman Hills (King and Fresno Counties) and Snowstorm Mountain (Lassen County), respectively; their locations are shown in Figure 13. The acquired wind data consisted of raw records collected by two met towers installed by DISGEN on behalf of the Energy Commission under Contract No. 500-01-042. The data were screened for quality, consistency and completeness. Summaries of the data were also compiled. This section highlights key characteristics of the wind resources for both sites.

Figure 13: Location of the Kettleman Hills and Snowstorm Mountain Towers



Source: AWS Truepower

Table 7 presents basic information about the towers, including their geographic coordinates, elevations, periods of record, and sensor heights provided by DISGEN, while Figure 13 shows the location of each tower.

Table 7: Wind Monitoring Summary

Mast	Site UTM Coordinates (WGS84, Zone 10)		Elevation (m)	Period of Record	Monitoring Heights (m)		
	Easting (m)	Northing (m)			Wind Speed	Wind Direction	Temp
Kettleman Hills	757482	3992756	360	1/18/05-5/29/06	50, 40, 30	49, 30	2
Snowstorm Mountain	723286	4502150	2000	9/2/05-4/26/06	50, 40, 30	50, 40	2

Source: AWS Truepower

The period of record for Kettleman Hills ran for approximately 17 months, beginning in January 2005, while the Snowstorm Mountain site operated for about 8 months, beginning in September 2005. Table 8 summarizes the wind resource characteristics observed over the periods of record, including the observed and annualized mean wind speeds, shear exponents, turbulence intensities, Weibull parameters, and air densities. The observed monthly mean wind speeds and data recovery percentages for both sites are presented in Table 9.

Table 8: Summary of Observed Wind Resource Characteristics

Parameter	Kettleman Hills	Snowstorm Mountain
Measurement Height (m)	50	50
Period of Record	18 Jan 2005 – 29 May 2006	2 Sep 2005 – 26 Apr 2006
Observed Mean Wind Speed (m/s)	4.21	6.69
Annualized Mean Wind Speed (m/s)	4.17	N/A
Data Recovery	95.3 percent	88.6 percent
Wind Shear Exponent* (*Only wind speeds > 4 m/s used in calculation.)	0.070 (50 m/40 m)	0.145 (50 m/40 m)
Turbulence Intensity at 15 m/s	0.12	0.11
Weibull Parameters (A/k)	4.86 m/s / 2.03	7.31 m/s / 2.30
Prevailing Wind Energy Direction	SSW	SW
Observed Air Density (kg/m^3)	1.212	1.008

Source: AWS Truepower

Table 9: Monthly Wind Speeds and Data Recoveries

Month-Year	Kettleman Hills		Snowstorm Mountain	
	50 m Speed (m/s)	Data Recovery (%)	50 m Speed (m/s)	Data Recovery (%)
Jan-05	2.92	42.8%	N/A	N/A
Feb-05	3.75	99.7%	N/A	N/A
Mar-05	3.78	100.0%	N/A	N/A
Apr-05	5.11	93.3%	N/A	N/A
May-05	4.86	100.0%	N/A	N/A
Jun-05	4.86	100.0%	N/A	N/A
Jul-05	4.30	99.5%	N/A	N/A
Aug-05	4.48	93.5%	N/A	N/A
Sep-05	3.92	86.7%	5.27	94.7%
Oct-05	4.22	96.5%	5.64	99.4%
Nov-05	3.58	92.2%	7.13	95.1%
Dec-05	3.55	86.8%	7.49	76.5%
Jan-06	3.71	96.4%	8.27	69.8%
Feb-06	3.53	99.9%	6.07	97.4%
Mar-06	4.47	93.3%	7.28	89.7%
Apr-06	4.88	96.1%	7.01	72.5%
May-06	4.81	86.3%	N/A	N/A
Average Speed	**4.21**	**95.3%**	**6.69**	**88.6%**

Source: AWS Truepower

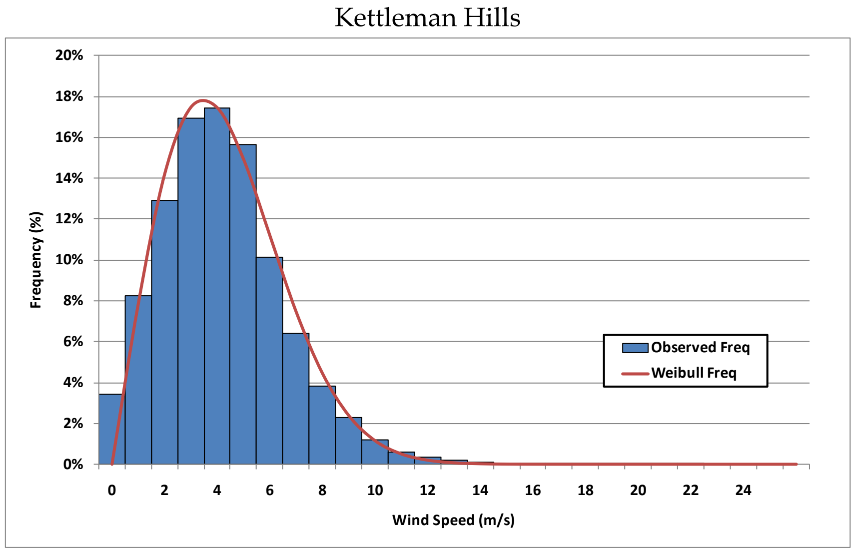
The observed 50 m mean wind speed was 4.21 m/s at Kettleman Hills (for 17 months) and 6.69 m/s at Snowstorm Mountain (for only 8 months). The annualized mean wind speed, which takes into account repeated months in the data record and weights each calendar month according to its number of days, was 4.17 m/s at Kettleman Hills. Due to the short period of record at Snowstorm Mountain, an annualized speed could not be determined.

Figure 14 below shows the observed frequency distribution and fitted Weibull curves for each site.

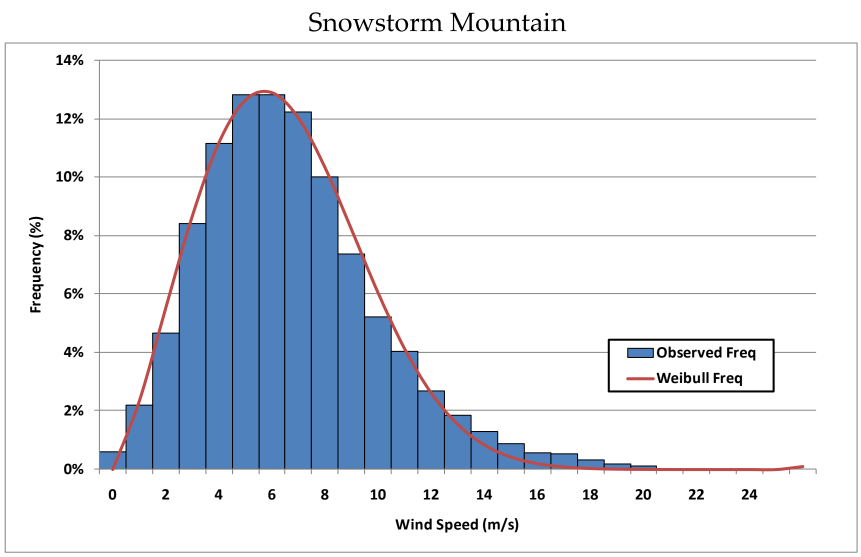
Figure 15 depicts the variation in average 50 m wind speed with time of day at Kettleman Hills. This site experiences its maximum winds during the late afternoon, with gradually diminishing winds overnight until the minimum is reached around 7 – 8 am local time.

Figure 16, the windier Snowstorm Mountain site experiences its peak winds beginning around noon, holding steadily through the afternoon until early evening when winds gradually diminish. Minimum speeds occur at mid-morning. The diurnal trending of wind shear exponents at both sites is shown on the same figures. In both cases, shear exponents are lowest during the day (when surface heating and vertical mixing of the lower atmosphere are strongest) and highest at night.

Figure 14: Observed Wind Speed Frequency Distribution and Fitted Weibull Curve

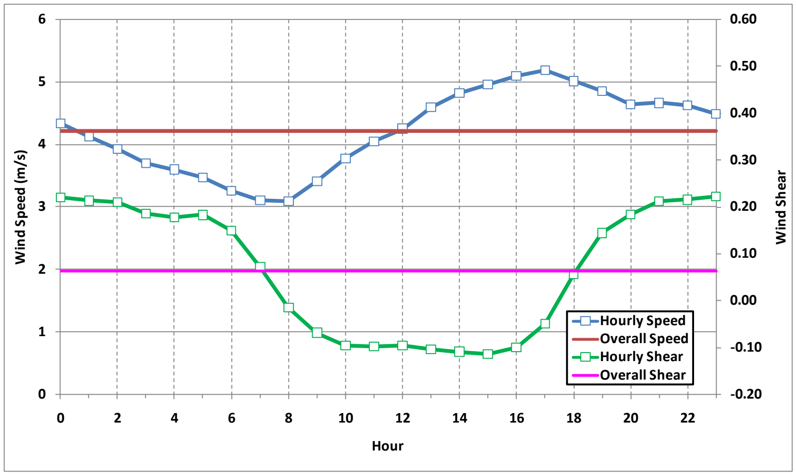


Source: AWS Truepower



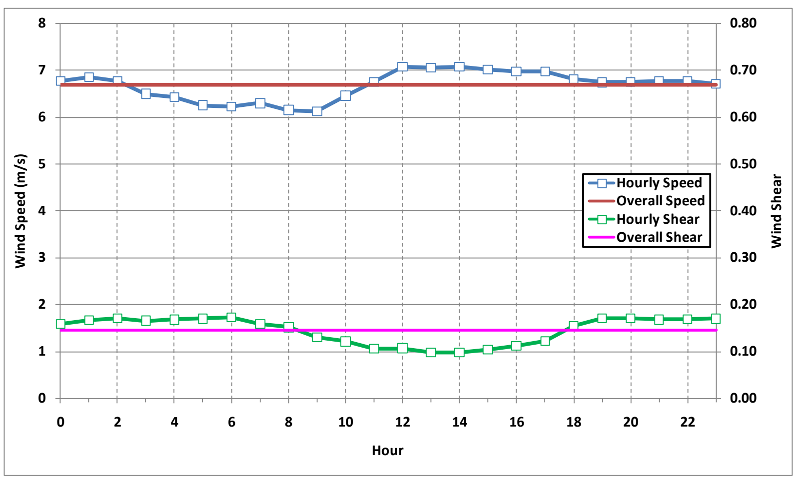
Source: AWS Truepower

Figure 15: Kettleman Hills 50 m Diurnal Wind Speed and Shear Distribution



Source: AWS Truepower

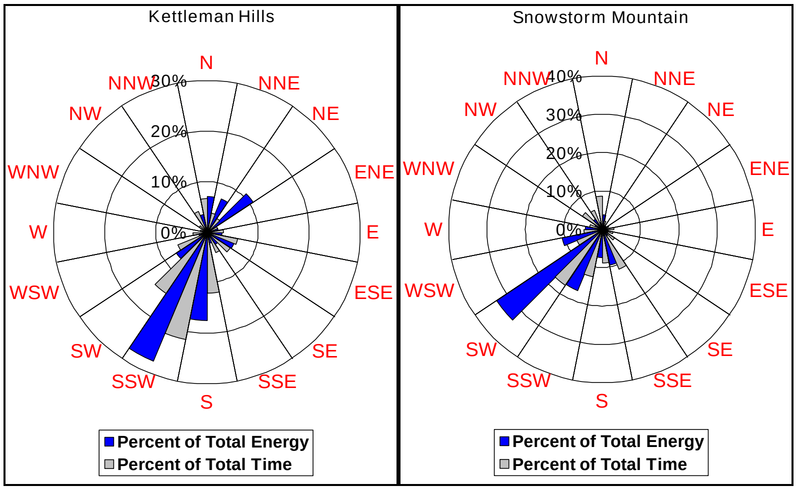
Figure 16: Snowstorm Mountain 50 m Diurnal Wind Speed and Shear Distribution



Source: AWS Truepower

The wind frequency and energy distribution by direction sector (wind rose) for both sites is plotted in Figure 17. The predominant wind direction sectors are south to southwest.

Figure 17. Kettleman Hills and Snowstorm Mountain Wind Rose



Source: AWS Truepower

CHAPTER 4:
Updated Regional Wind Maps

In a previous project for the California Energy Commission entitled "New Wind Energy Resource Maps of California" (Contract #500-01-009), TrueWind Solutions (subsequently AWS Truewind, and now AWS Truepower) used its MesoMap® system to produce highly detailed maps and data files of the State of California's wind energy resources. The underlying purpose of the project was to encourage the development of wind energy in the State by helping companies and individuals identify promising wind project sites with a minimum of effort. The maps were validated using wind measurements from 266 locations throughout the State, including airports, ocean buoys, and towers instrumented specifically for wind resource assessment.

Under the current project, among other tasks, regional wind maps were to be updated using site-specific wind data gathered within the two designated focus areas. The updated maps were also to be incorporated into the previously developed statewide wind resource map. This chapter describes the regional wind mapping methodology and presents differences and improvements made to the high-resolution (200 m) wind maps in the two focus areas.

The MesoMap system creates a wind resource map in several steps. First, the MASS model (Mesoscale Atmospheric Simulations System) simulates weather conditions over 366 days selected from a 15-year period. The days are chosen through a stratified random sampling scheme so that each month and season is represented equally in the sample; only the year is randomized. Each simulation generates wind and other weather variables (including temperature, pressure, moisture, turbulent kinetic energy, and heat flux) in three dimensions throughout the model domain, and the information is stored at hourly intervals. When the runs are finished, the results are summarized in files, which are then input into the WindMap program for the final mapping stage. The two main products are usually (1) color-coded maps of mean wind speed and power density at various heights above ground and (2) data files containing wind speed and direction frequency distribution parameters.

Once completed, the maps and data can be compared with land and ocean surface wind measurements, and if significant discrepancies are observed, the wind maps can be adjusted. The most common sources of validation data are tall towers instrumented for wind energy assessment and standard meteorological stations. The validation is usually carried out in the following steps:

1. Station locations are verified and adjusted, if necessary, by comparing the quoted elevations and station descriptions against the elevation and land cover maps. Where there are obvious errors in position, the stations are moved to the nearest point with the correct elevation and surface characteristics.

2. The observed mean speed and power are adjusted to the long-term climate norm and then extrapolated to the map height using the power law. Often, for the tall towers, little or no extrapolation is needed. Where multi-level data are available, the observed mean

wind shear exponent is used. Where measurements were taken at a single height, the wind shear is estimated from available information concerning the station location and surroundings.

3. The predicted and measured/extrapolated speeds are compared, and the map bias (map speed minus measured/extrapolated speed) is calculated for each point. If there are enough towers, the mean bias and standard deviation of the biases is calculated. Note that the bias and standard deviation may reflect errors in the data as well as the map.

4. If a pattern of bias is detected, the maps are adjusted to reduce or eliminate the discrepancy.

The MesoMap system has been validated in this fashion using data from well over 1000 stations worldwide. The typical standard error, after accounting for uncertainty in the data, has been found to be 5-7 percent of the mean speed at a height of 50 m.

4.1 Regional Focus Area Map Updates - Tehachapi Pass Area

The high (200 m grid) resolution speed map of Tehachapi Pass and the map of the ratio of the new to old speeds are shown in:

Figure 18 and Source: AWS Truepower

Figure 19 at a reference height of 70 m.

The Tehachapi tower was located just to the east of the highest winds found in Tehachapi Pass, at the edge of a sharp east-west wind speed gradient with the lower wind area to the east. Since the delivery of the high resolution wind map of the area in 2006, additional wind data near this tower has been evaluated. The results from the tower were combined with prior experience in the local area to create a variable wind speed adjustment of 5 percent - 10 percent. Based on the new data, it was concluded that the previous map underestimated the magnitude of the wind resource across the highest wind area, as well as the spatial extents (northeast - southwest) of the highest winds. Comparisons between the previous and updated maps can be found in Table 10.

Table 10: Tehachapi Pass Area Map Update Comparison

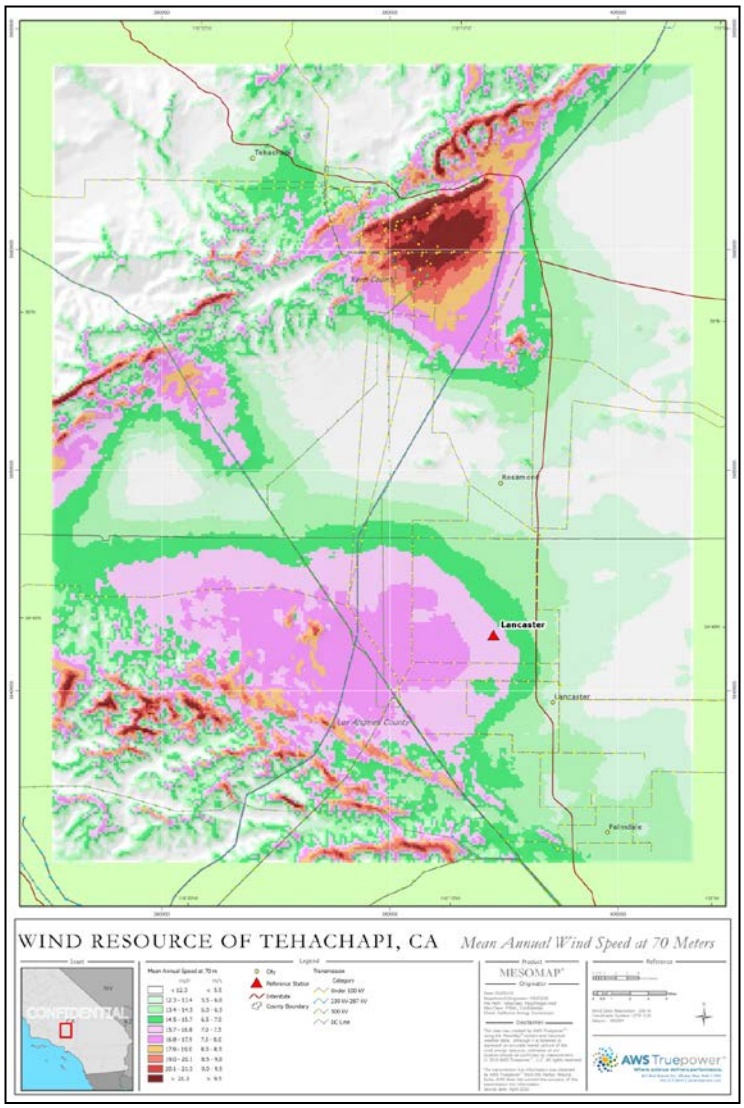
Tower	Projected 70-m Speed (m/s)	2007 70-m Map Speed (m/s)	2010 70-m Map Speed (m/s)	Bias (m/s)
Tehachapi	9.12	8.08	8.94	-0.18

Source: AWS Truepower

It is important to note that the modeled wind speed does not align perfectly with the tower's speed results. As mentioned above, evaluated data from other sources in this area support a wind speed increase from the previous map. However, the exact magnitude of increase is not clear. Much like wind flow models, tower measurements carry their own sources of uncertainty such as instrumentation, representativeness of monitoring period, and wind shear. With this in mind, all of the data available near the tower was used to produce the wind speed adjustment, and thus provide a statistically robust estimate of the wind resource with the lowest possible overall uncertainty.

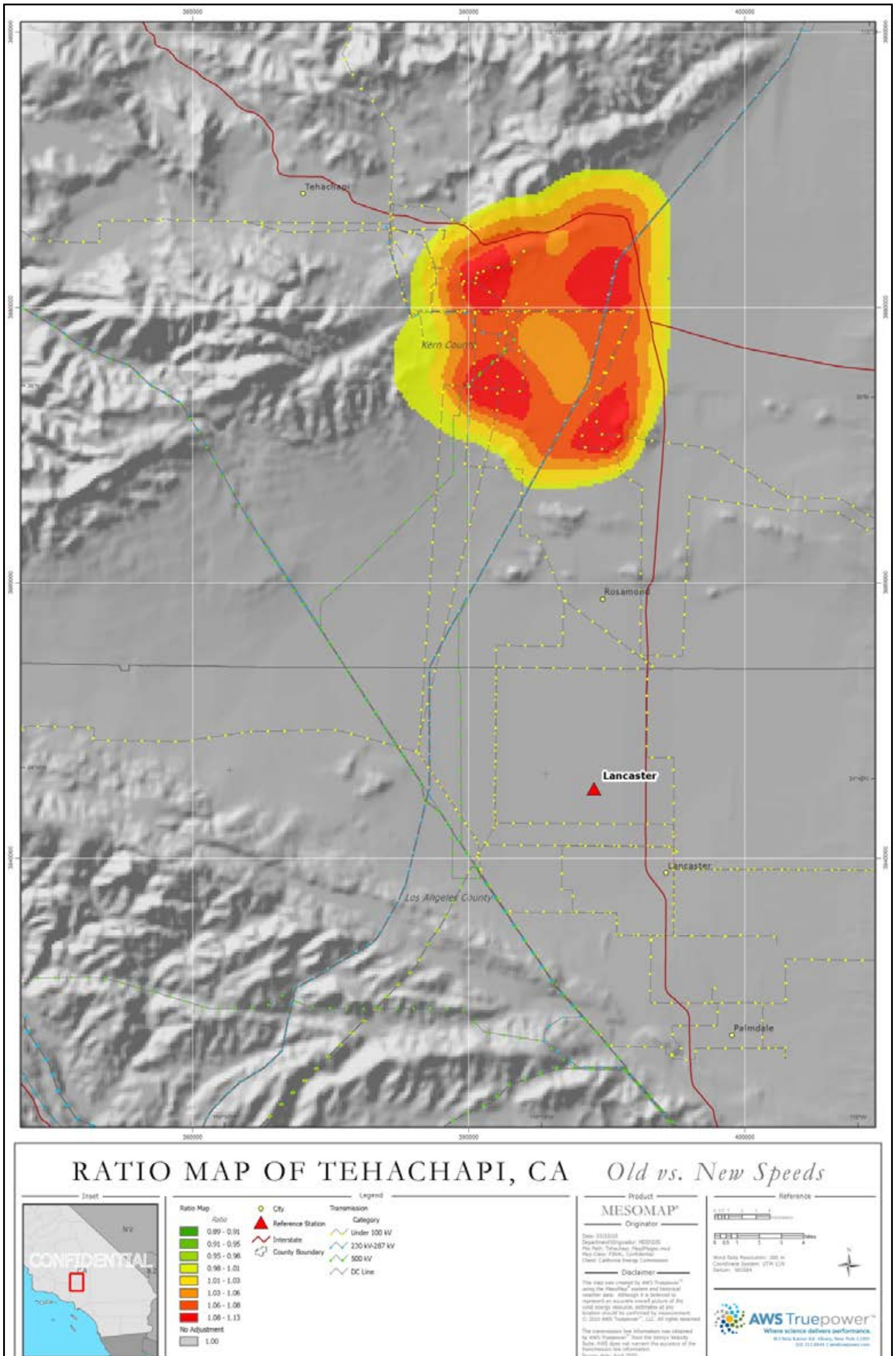
Adjustments were only made to the high wind area in Tehachapi Pass; it is felt that the relationship between the tower and the wind map is necessarily indicative of the model performance across the larger area away from the Pass. The adjusted wind speeds were blended with the previous values outside of the Pass.

Figure 18: Mean Annual Wind Speed at 70 m, Tehachapi Pass Focus Area



Source: AWS Truepower

Figure 19: Ratio Map, Old vs. New Wind Speeds, Tehachapi Pass Focus Area



Source: AWS Truepower

4.2 Regional Focus Area Map Updates – Imperial Valley

The high resolution speed map of Imperial Valley and the map of the ratio of the new to old speeds are shown in Figure 20 and Figure 21. The met tower was located in the elevated terrain to the west of Imperial Valley. Additional wind data in the region within 10-20 km of the tower was evaluated since the delivery of the high resolution wind map of the area in 2006. An apparent relationship between accuracy of the model and elevation was found: the model bias is negative at higher elevations (model is low) and positive at lower elevations (model is high). Using this relationship, an adjustment was created that reduced the map wind speed in the vicinity of the tower by 7.4 percent and increased the speed at the higher elevations by up to 5 percent. Based on the new data, it is concluded that the previous map underestimated the wind speed change with elevation on the west side of Imperial Valley. Comparisons between the previous and updated maps can be found in Table 11.

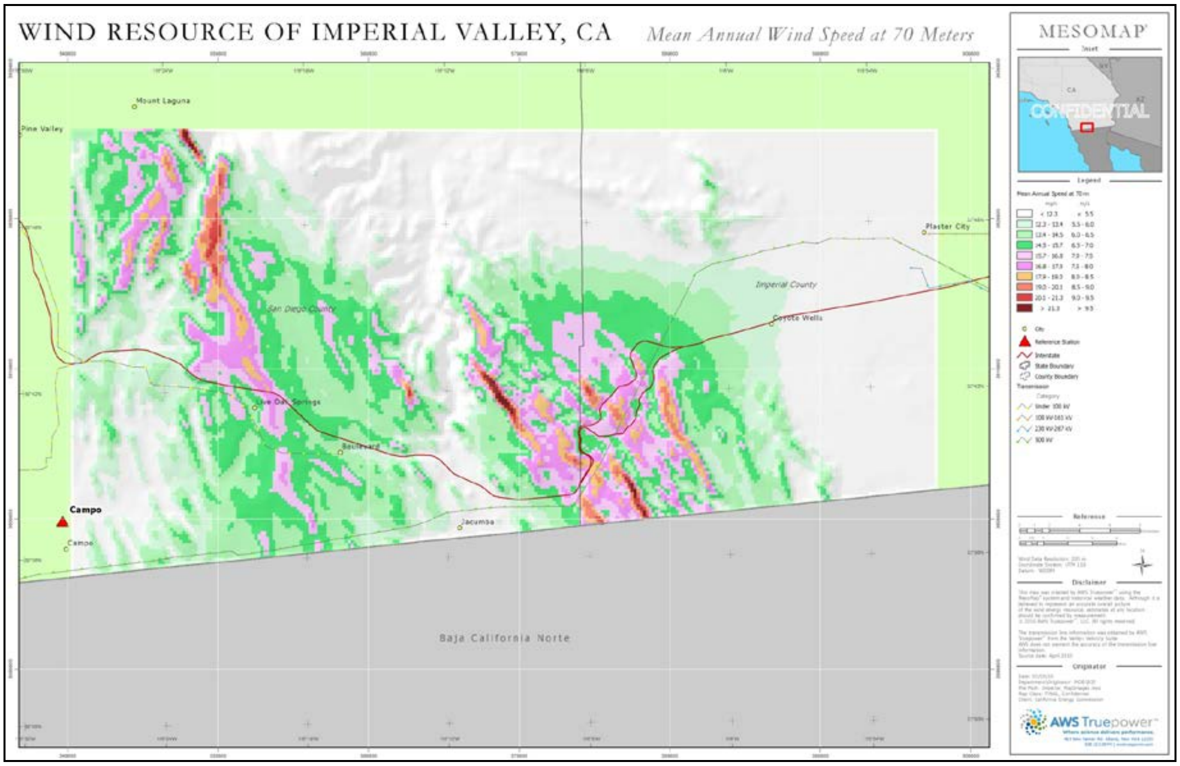
Table 11: Imperial Valley Map Update Comparison

Tower	Projected 70-m Speed (m/s)	2007 70-m Map Speed (m/s)	2010 70-m Map Speed (m/s)	Bias (m/s)
Imperial Valley	7.33	8.01	7.42	+0.09

Source: AWS Truepower

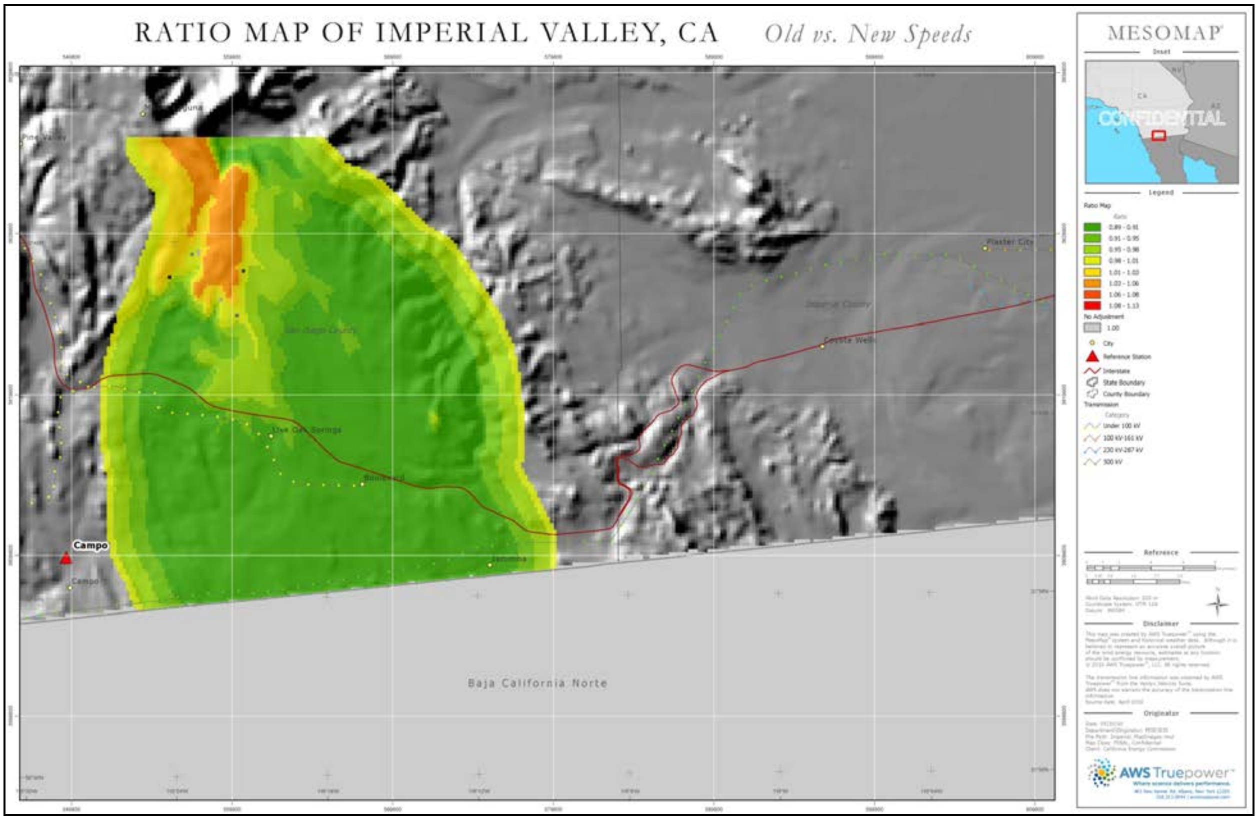
Adjustments were only made to the area within 20 km of the Imperial Valley tower, and were primarily focused on areas where measurements had been evaluated by AWST. The adjusted wind speeds were blended with the previous values outside of the adjustment zone.

**Figure 20: Mean Annual Wind Speed at 70 m,
Imperial Valley Focus Area**



Source: AWS Truepower

Figure 21: Ratio Map, Old vs. New Wind Speeds, Imperial Valley Focus Area



Source: AWS Truepower

CHAPTER 5: Unusual Weather Events

Unusual and episodic meteorological events such as extreme wind shear, atmospheric flow separation within the rotor plane heights of a wind turbine, and sudden wind speed swings (ramping events) are important considerations when characterizing the quality of prospective sites for wind energy development. Such events can have direct and indirect impacts on project performance and safety, equipment reliability, and transmission grid stability; they can also impact various stakeholders, including wind project developers and owners, O&M providers, turbine manufacturers, and transmission system operators. This chapter presents the findings of an analysis of unusual meteorological events for the Tehachapi Pass and Imperial Valley focus areas using the years' worth of measured meteorological data, which was summarized in Chapter 3. The objective of this analysis is to characterize the nature and frequency of unusual meteorological events within these areas and to make this information accessible to stakeholders.

Unusual meteorological events considered in this analysis were defined generically as the following: 1) high wind speeds and maximum wind gusts; 2) extreme wind and directional shear; 3) significant short-term changes in wind speed (such as ramp events); 4) temperature extremes; and 5) extreme turbulence intensity. The following sections provide a quantitative definition of these events, how they impact the quality of the wind resource, and their frequency in each focus area. This analysis relied primarily on the tower measurements but was supplemented by the sodar data for a portion of the year to verify events observed by the towers. The sodar measurements were a useful addition to the meteorological monitoring program because they measured the wind profile up to and above the hub height of modern utility-scale wind turbines, which ranges from 65 to 100 m.

5.1 High Wind Events

The power generated by a wind farm at any given time is, for the most part, directly related to the wind speed. Extreme wind speeds, such as values in excess of 22-25 m/s over a 10-minute interval, or maximum 2-second wind gusts in excess of 30 m/s, can cause turbines to shut down, resulting in sudden drops in energy generation. Table 12 and Table 13 provide the observed 2-second maximum wind gust and the corresponding 10-minute average wind speed and air density on a monthly basis for the Tehachapi Pass and Imperial Valley towers, respectively, during the one-year period from October 2007 to September 2008. Both towers recorded maximum gusts and 10-minute average speeds of roughly 40 m/s and 33 m/s, respectively, during the one-year period. The monthly distribution of maximum 10-minute wind speeds and gusts generally follows the average wind speed pattern observed during the course of the year at each site.

For most wind turbines, once the wind speed measured on the turbine nacelle exceeds the turbine's design cut-out speed (the highest wind speed at hub height at which the wind turbine is designed to produce power in the case of steady wind without turbulence) and the machine shuts down, the control software waits until the speed drops below a lower speed threshold (the reset-from-cut-out speed) before allowing the turbine to restart. A loss is usually assumed that accounts for the energy lost in this hysteresis loop. This loss is calculated from wind data collected at the site and the manufacturer's specified cut-out and reset-from-cut-out speeds.

Table 12: Tehachapi 2-Second and 10-Minute Maximum Observed Wind Speeds (49.1 m)

Month	2-Second Max Wind Gust (m/s)	10-Minute Average Wind Speed (m/s)	Air Density (kg/m³)
Oct-07	33.23	25.34	1.10
Nov-07	27.48	21.15	1.12
Dec-07	33.59	27.25	1.12
Jan-08	36.31	26.43	1.13
Feb-08	32.44	24.32	1.12
Mar-08	33.59	25.55	1.12
Apr-08	35.16	27.69	1.12
May-08	36.31	31.46	1.08
Jun-08	39.35	33.88	1.07
Jul-08	27.48	18.87	1.12
Aug-08	27.48	20.50	1.07
Sep-08	27.93	20.64	1.22

Source: AWS Truepower

Table 13: Imperial Valley 2-second and 10-minute Maximum Observed Wind Speeds (50 m)

Month	2-Second Max Wind Gust (m/s)	10-Minute Average Wind Speed (m/s)	Air Density (kg/m³)
Oct-07	26.76	21.10	1.07
Nov-07	26.76	20.66	1.08
Dec-07	34.41	27.87	1.08
Jan-08	37.80	32.87	1.09
Feb-08	39.77	32.76	1.08
Mar-08	27.48	22.73	1.08
Apr-08	34.05	29.69	1.10
May-08	27.12	24.02	1.08
Jun-08	26.76	20.85	1.05
Jul-08	16.05	11.71	1.00
Aug-08	18.33	12.82	1.04
Sep-08	19.07	11.19	1.04

Source: AWS Truepower

The number of high wind cut-out events per month for both towers, average duration of events per month, and the maximum event duration, are found in Table 14. These statistics were calculated using the GE 1.5 sle (1.5 MW) model turbine's high wind cutout and restart specifications of 25 m/s (10-minute interval) and 22 m/s (5-minute interval), respectively. These specifications are typical of other megawatt-scale commercial wind turbine models.

Between October 2007 and September 2008, the Tehachapi tower experienced 52 separate high wind shutdown events, while only 15 were observed at the Imperial Valley tower. The maximum duration of any event was 470 minutes (7.8 hours) at the Tehachapi tower and 940 minutes (15.7 hours) at the Imperial Valley tower. The average duration of high each wind shutdown event per month ranged from 142 minutes (2.4 hours) to 305 minutes (5.1 hours) at the Tehachapi tower and 20 minutes (0.3 hours) to 655 minutes (10.9 hours) at the Imperial Valley tower.

Table 14: Frequency of High Wind Shutdown Events per Month

	Tehachapi			Imperial Valley		
Month	Tehachapi Frequency of Events	Average Duration of Events (minutes)	Maximum Duration of Event (minutes)	Imperial Valley Frequency of Events	Average Duration of Events (minutes)	Maximum Duration of Event (minutes)
Oct-07	9	184	430	0	0	0
Nov-07	0	0	0	0	0	0
Dec-07	4	183	430	2	655	830
Jan-08	2	305	470	5	436	940
Feb-08	2	210	320	6	332	940
Mar-08	11	142	410	1	20	20
Apr-08	8	180	340	1	470	470
May-08	9	233	410	0	0	0
Jun-08	7	198	440	0	0	0
Jul-08	0	0	0	0	0	0
Aug-08	0	0	0	0	0	0
Sep-08	0	0	0	0	0	0

Source: AWS Truepower

The expected long-term (50-year) maximum 10-minute wind speed at a proposed project site is used as an input to determine turbine suitability. This value is often calculated using the on-site time series data and the Gumbel distribution, a method used to determine extreme values. Table 15 provides the observed 10-minute extreme wind speeds along with the 10-, 20-, and 50-year return period estimated maximum 10-minute wind speeds for the Tehachapi and Imperial Valley towers. The results indicate that maximum 10-minute wind speeds should exceed 50 m/s at both sites over a period of 20 years or more. The Tehachapi site is expected to observe more extreme winds than the Imperial Valley focus area.

Table 15: Observed and Projected Extreme 10-minute Wind Speeds

Tower	Observed 10-min Maximum Speed (m/s)	Projected 10-year Max 10-min Speed (m/s)	Projected 20-year Max 10-min Speed (m/s)	Projected 50-year Max 10-min Speed (m/s)
Tehachapi (49.1 m)	34.3	51	55	59
Imperial Valley (50 m)	34.0	45	49	54

Source: AWS Truepower

5.2 Wind Shear

Significant changes in wind speed or wind direction across the turbine rotor plane can result in uneven loads on the turbine, potentially impacting its performance in the short-term and reducing turbine component lifetimes. The observed wind speed exponents of 0.14 at the Tehachapi tower and 0.09 at the Imperial Valley tower are consistent with the surrounding area and surface roughness. The standard deviation of the wind shear between the top and bottom level anemometers was calculated from each tower data set and threshold values were established for one, two, and three standard deviations from the observed mean. The results are presented in Table 16.

Table 16: Shear Values

Tower	Shear Heights	Observed Shear	Mean Shear + / - One Standard Deviation	Mean Shear + / - Two Standard Deviations	Mean Shear + / - Three Standard Deviations
Tehachapi	49.1 m / 29.6 m	0.14	0.26 / (0.019)	0.38 / (-0.101)	0.50 / (-0.221)
Imperial Valley	50.0 m / 30.0 m	0.09	0.22 / (-0.037)	0.34 / (-0.163)	0.47 / (-0.289)

Source: AWS Truepower

For this analysis, we elected to define extreme wind shear as those values exceeding three standard deviations from the mean. At both the Tehachapi and Imperial Valley towers, only 2.0 percent of the observations out of the entire period of record exceeded this threshold. The wind shear values were determined for cases where the top-level was greater than or equal to 4 m/s. These results indicate that extreme shear values will likely not be an important issue at either site.

Table 17 provides the observed extreme positive and negative wind shear values at each monitoring site as recorded by the towers. The values were determined for cases where the top-level wind speed was greater than or equal to 4 m/s. We evaluated available sodar data for these particular events, as well as for several other extreme cases, to examine the shear trends above tower top. In most negative wind shear cases, the sodar indicated an even faster drop in wind speed above tower top. Sodar data for the high shear cases were more difficult to interpret since valid sodar data at heights above the tower were somewhat limited. It is known that the dry atmosphere in southern California will often limit the altitude performance of the sodar.

Table 17: Tehachapi and Imperial Valley Extreme Wind Shear Outliers

Tower	Shear Heights	Top-level Wind Speed (m/s)	Extreme Positive Wind Shear Exponent	Top-level Wind Speed (m/s)	Extreme Negative Wind Shear Exponent
Tehachapi	49.1 m / 29.6 m	4.1	1.42 (1/15/08 at 4:20 PST)	4.1	-0.86 (10/31/07 at 19:30 PST)
Imperial Valley	50 m / 30 m	4.4	1.48 (6/5/08 at 5:00 PST)	8.1	-0.99 (12/9/07 at 9:00 PST)

Source: AWS Truepower

Wind direction can change with height as a result of a reduction in surface-induced frictional effects. Changes in wind direction are more commonly found under relatively stable atmospheric conditions. For this analysis, we looked at how often the upper-level and lower-level wind vanes on each tower varied by more than one direction sector, defined here as 22° in a 16-sector rose. The main finding at the towers and sodar units was that extremes in directional shear between the top and bottom monitoring levels on the same tower were more prevalent during the overnight hours, particularly during the spring months. The higher concentration of events during the spring season may be caused by the continental/marine temperature gradient nearing its maximum.

During the one year period of record at the Tehachapi focus area, there were 46 instances when the difference in wind direction between the upper-level (48 m) and lower-level (31 m) wind vanes was greater than 22° when the top-level (49.1 m) wind speed was greater than or equal to 4 m/s. Of these 46 occurrences, the majority of them were observed during the late night and early morning hours, while 32 of the 46 events occurred from March through June. At the Imperial Valley tower, there were 117 instances when the difference between the upper-level (50 m) and lower-level (30 m) wind vanes differed by the 22° threshold at wind speeds greater than or equal to 4 m/s. Similar to the Tehachapi tower, the majority of these events occurred between midnight and 7 am Pacific Standard Time (PST). Of the total occurrences, 44 were observed between March and June. The Imperial Valley site showed a higher percentage of changes in wind direction between monitoring levels compared to the Tehachapi site. One explanation for this is the fact that the Imperial Valley site, overall, experiences lower mean wind speeds than the Tehachapi Pass site. Directional shear has a higher frequency at lower wind speed sites. Of the 117 events that occurred at the Imperial Valley tower, 80 percent of them occurred when the wind speed was relatively low, between 4 and 5 m/s.

Also examined was the change in wind direction from one 10-minute observation to the next. Significant changes in wind direction are not uncommon at very low wind speeds. For this exercise, low wind speeds are considered to be less than 4 m/s. Large directional shear at higher speeds are often caused by frontal passages or severe weather events. These directional shifts can result in a reduction in the power output of a turbine since it takes time for the machine to reorient itself to the new wind direction. When the top-level anemometer recorded speeds greater than or equal to 4 m/s, wind direction changes of one sector or more were observed roughly 2 percent of the time at the Tehachapi site and 1 percent at the Imperial Valley site.

5.3 Ramp Events

The likelihood of sudden excursions in wind power output caused by significant short-term changes in wind speed, known as ramp events, is important to understand in areas where wind generation is expected to make a significant penetration into the electric grid. Meteorological events that typically cause rapid short-term changes in wind speed include frontal passages, thunderstorms, and the low-level jet. Frontal systems, or air mass discontinuities, can move through the project area with an accompanying fall/rise in atmospheric pressure, which can result in a rapid wind speed increase followed by a (more gradual) decrease. Thunderstorms, which occur on the mesoscale, can move in any direction and at speeds in excess of 25 m/s. The influence of each of these phenomena varies by region. For example, ramp events induced by thunderstorm outflow boundaries are commonly found in the Midwest and the Plains States, but are rare in southern California.

Ramp-down events occur as well. These generally occur with the rapid slackening of a pressure gradient or the passage of a local pressure couplet, which can be associated with the events described above. Ramp-down events can also be caused by high wind speeds that exceed the cut-out speed of wind turbines as discussed in the high wind events section.

In general, ramp-up events occur more often in the evening hours due to convection being climatologically favored at this time. There is also an increase in the frequency of ramp-up events from late winter through summer. This is also consistent with the dominance of convection as a cause of ramp-up events.

Changes in mean wind speed over 10-minute and hourly intervals were determined for each tower location to assess the potential for large fluctuations in wind speed and corresponding energy production. Table 18 provides the observed maximum 10-minute and hourly wind speed changes at each tower. Significantly larger short-term changes in speed were observed at the Tehachapi site compared to the Imperial Valley. This is a known characteristic of the Tehachapi Pass. Fortunately, the output of a wind plant shows much less variability than indicated by measurements from a single tower because of the spatial diversity of the wind resource.[2]

[2] Wan, Y. "A Primer on Wind Power for Utility Applications," NREL Technical Report, December 2005.

Table 18: Maximum 60-minute and 10-minute Up and Down Wind Events

Tower	Hourly Max Up Ramp (m/s)	10 minute Max Up Ramp (m/s)	Hourly Max Down Ramp (m/s)	10 minute Max Down Ramp (m/s)
Tehachapi	17.5	13.8	-17.2	-12.6
Imperial Valley	9.6	7.3	-8.7	-8.3

Source: AWS Truepower

The max up and down ramps that occurred at the Tehachapi site appear to have been caused by the passage of frontal systems through the region along with differences in diurnal heating. At the Imperial Valley tower, the events identified in Table 18 can also be attributed to frontal passages along with possible thunderstorm activity. Both sites experienced a maximum frequency of ramp-up events during the spring and summer months.

The sodar data presented no apparent trend in the presence of ramp events with the hour of day or day of year for the given sites. Ramp events were occasionally accompanied by changes in wind direction, but not consistently.

5.4 High Temperature Events

Similar to high wind speed conditions, turbine manufacturers also employ algorithms that are designed to shut down wind turbines under extreme temperature conditions to minimize damage to system components. For this analysis, the number and duration of extreme temperature events were defined using the high and low temperature thresholds of +40°C and -15°C, respectively, for the GE 1.5 sle turbine. Table 19 below provides the number and maximum duration of high temperature events by month for the Tehachapi and Imperial Valley sites.

During the one year period of record, both towers experienced five separate high temperature shutdown events, occurring in the July/August timeframe. The maximum duration of any event for the Tehachapi and Imperial Valley towers was 490 minutes (8.2 hours) and 410 minutes (6.8 hours), respectively. These shutdown events occurred when wind speeds were primarily outside the normal wind speed operation range and will likely have little impact on overall energy production at either the Tehachapi or Imperial Valley sites.

Table 19: Frequency of High Temperature Shutdown Events per Month

Month	Tehachapi Frequency of Events	Maximum Duration of Event (minutes)	Imperial Valley Frequency of Events	Maximum Duration of Event (minutes)
Oct-07	0	0	0	0
Nov-07	0	0	0	0
Dec-07	0	0	0	0
Jan-08	0	0	0	0
Feb-08	0	0	0	0
Mar-08	0	0	0	0
Apr-08	0	0	0	0
May-08	0	0	0	0
Jun-08	0	0	0	0
Jul-08	4	490	0	0
Aug-08	1	200	5	410
Sep-08	0	0.0	0	0

Source: AWS Truepower

5.5 Turbulence Intensity

The turbulence intensity measures fluctuations in the wind speed recorded by an anemometer in each 10-minute interval as a fraction of the average speed. Turbulence intensity values below 0.10 are considered low, values between 0.10 and 0.15 are moderate, and high turbulence intensity corresponds to values above 0.15. An understanding of the turbulence intensity at a project site is important because it directly affects the fatigue loads of a number of major components in a wind turbine. The load cases are defined by the turbulence intensity at 15 m/s. Depending on the edition of the IEC standard used for the turbine certification, turbine manufacturers either use the average turbulence intensity or the sum of the average plus one standard deviation (characteristic turbulence intensity).

The observed turbulence intensities at 15 m/s, 0.11 at Tehachapi and 0.09 at Imperial Valley, are relatively low and consistent with each site's surface roughness. The standard deviation of turbulence intensity was calculated from each tall tower data set and threshold values were established for one, two, and three standard deviations from the mean. The results are presented in Table 20. The distributions as a function of wind speed at each site are presented in the charts in Figure 22 and Figure 23.

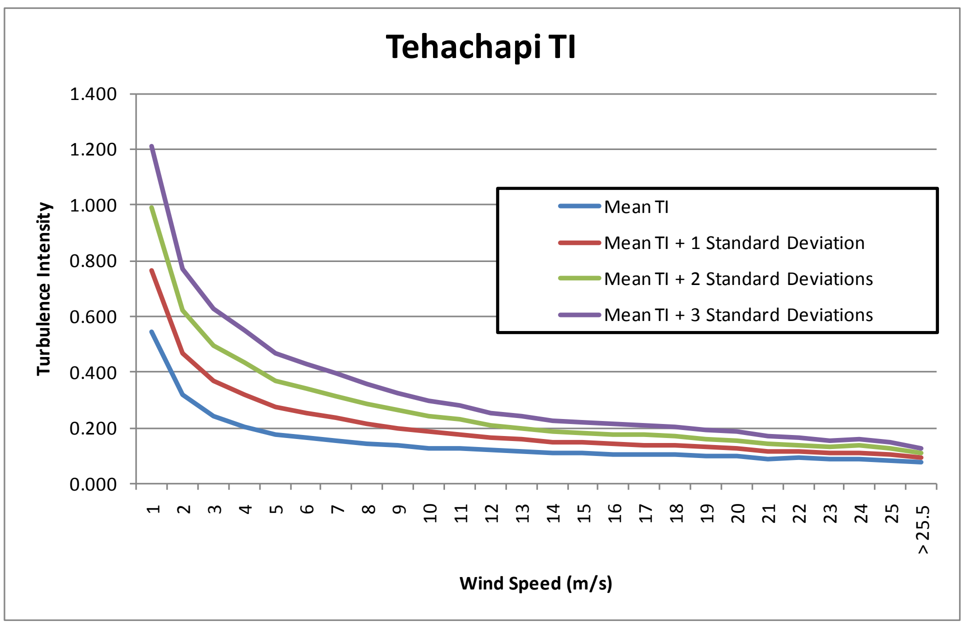
Table 20: Turbulence Intensity Values

Tower	Observed (15 m/s)	Mean TI + One Standard Deviation	Mean TI + Two Standard Deviations	Mean TI + Three Standard Deviations
Tehachapi	0.11	0.15	0.19	0.22
Imperial Valley	0.09	0.11	0.14	0.17

Source: AWS Truepower

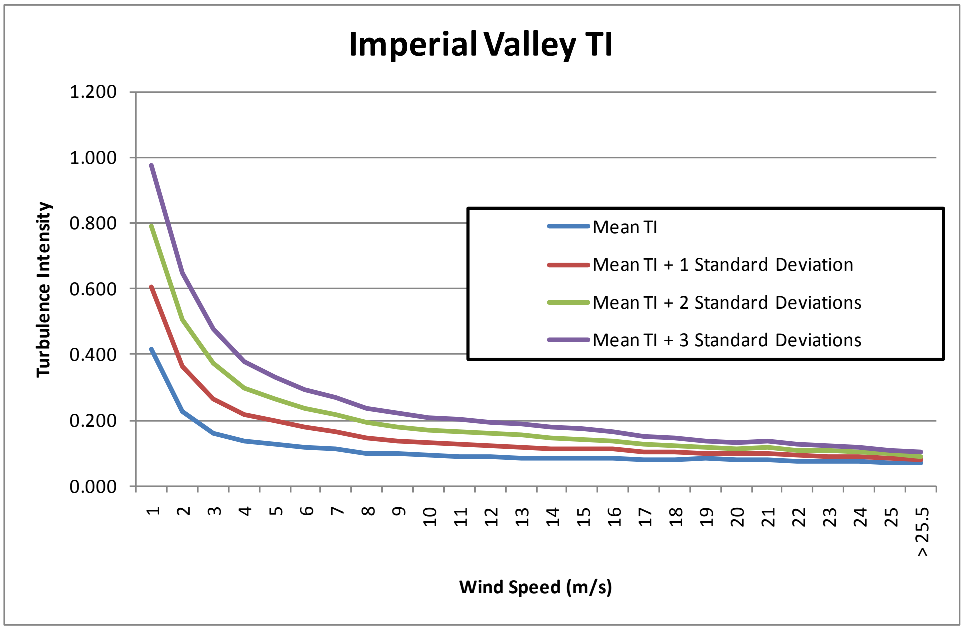
For this analysis, we elected to define turbulence intensity outliers as those values exceeding three standard deviations from the mean. At the Tehachapi tower, only 0.10 percent of the observations exceeded this threshold, while at the Imperial Valley tower, only two 10-minute observations out of the entire period of record exceeded the three standard deviation threshold. These results indicate that extreme turbulence intensity will likely not be an important issue at either site.

Figure 22: Tehachapi Turbulence Intensity Distribution



Source: AWS Truepower

Figure 23: Imperial Valley Turbulence Intensity Distribution



Source: AWS Truepower

5.6 Environmental Factors

Depending on location, other environmental factors, including icing, snowfall, and lightning, can affect wind plant operation and performance. Ice accretion on the turbine blades can impact energy output, while snowfall can impede site access in some instances. Lightning can damage turbine components and cause electrical faults resulting in plant shutdowns. Fortunately, the occurrence of these meteorological phenomena in southern California is quite rare, so they are not expected to adversely impact a turbine project in this region.

CHAPTER 6:
Time-of-Use Data Development

In addition to areas of California where large-scale wind farm development has significant potential, there is also interest in the wind characteristics in the vicinity of local communities where distributed, community- and small-scale wind applications are under consideration. Such applications are typically customer sited and connected to the grid on the customer's side of the meter. Because of the cost and time requirements of a wind resource assessment campaign, project considerations of this size scale often rely instead on map-based resource predictions to estimate the annual energy production and economic viability of a project. The existing wind resource map of California, together with the underlying data used to create it, provides a source of wind statistics at a relatively fine spatial resolution (200m by 200m) to facilitate an assessment of proposed distributed wind applications.

For a set of communities identified by the Energy Commission, an hourly time series data base was created for a "typical" year consisting of average wind speed, wind direction, and air temperature for hub heights of 30 m and 50 m. The provision of hourly values throughout the year is intended to enable other parties to analyze the time-of-use (load matching) generation, together with annual and seasonal outputs, from a selected wind turbine model.

The selection of communities for which wind data files were created involved a screening process that began with 32 candidate locales that had expressed interest to the Energy Commission in community-scale wind energy. Using the California wind map, the locales were assessed for the availability of wind resources of at least 5 m/s at a hub height of 50 m. Following an assessment of the amount of land area available near each community possessing this wind resource, and other land use considerations, a final list of nine communities was assembled. The selected locales are listed in Table 21 and shown in Figure 24.

The hourly time series data for a typical year were derived for each selected community from a modeled and gridded 12-year climatological dataset created by AWST (known as windTrends) for the entire United States. The dataset was developed using a combination of historical measured and modeled data synthesized from federal sources and a quality screening process to eliminate biases. To construct a typical meteorological year for each community, the full 12-year period of data for the nearest grid cell was examined. Each individual month in the dataset was compared to the long-term average conditions for that month. For example, the average wind speed of each of the 12 Januaries was compared to the average of all the Januaries. The individual January coming closest to the climatological average speed was then selected as the first month of the typical year. The same process was followed for the remaining 11 months. Consequently, a typical year was composed of an assortment of 'average' months from various years. Table 22 lists the individual months chosen to compile the typical year for each community.

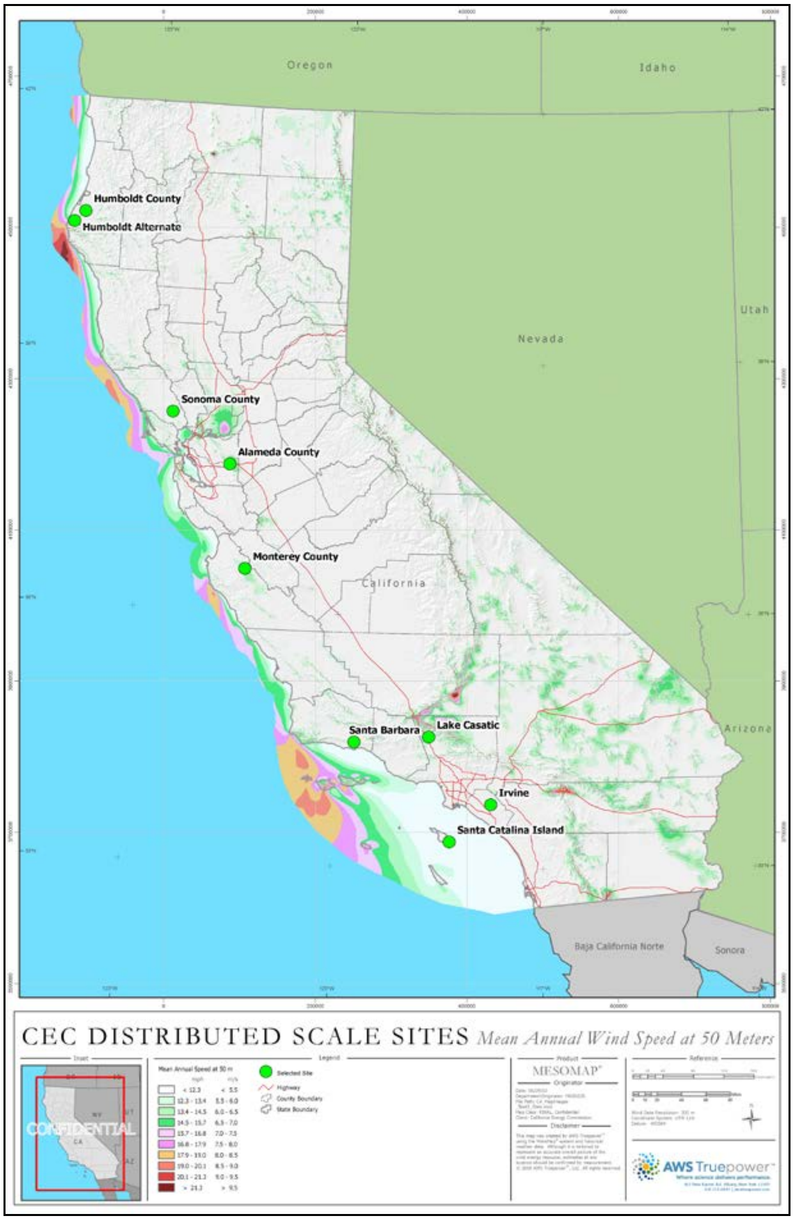
The deliverable for this task was a series of Excel spreadsheets containing 8,760 hourly records for the nine selected communities. The records give values at 30 m and 50 m for wind speed, direction, air temperature, and air density.

Table 21: Location of Nine Selected Sites

Location	Latitude	Longitude
Alameda County	37.7349	-121.6829
Humboldt County	40.6299	-124.1230
Humboldt Alternate	40.5010	-124.2828
Irvine	33.7637	-117.7416
Lake Castaic	34.5610	-118.6410
Monterey County	36.5027	-121.3858
Santa Barbara	34.4821	-119.7146
Santa Catalina Island	33.3141	-118.3286
Sonoma County	38.3268	-122.5766

Source: AWS Truepower

Figure 24: Selected Sites



Source: AWS Truepower

Table 22: Typical Meteorological Year Composition

Month	Alameda	Humboldt	Humboldt Alternate	Irvine	Monterey	Lake Castaic	Santa Barbara	Santa Catalina	Sonoma
Jan	1999	1999	1999	2001	1997	1999	2003	2005	1998
Feb	2007	2006	2006	2008	2004	1998	2004	1999	2003
Mar	2005	2005	2003	2007	2002	2002	2000	1998	2002
Apr	2000	1998	2001	2005	2000	2005	2000	2005	2003
May	2002	2005	2005	2000	2003	2005	1999	2003	1998
Jun	2003	2007	2005	2001	2007	2007	1998	1999	1999
Jul	2004	2007	2003	2008	2003	2006	2008	1998	2000
Aug	2000	2007	2007	2005	1997	2007	2000	1998	1997
Sep	2006	1998	1997	2005	2002	2003	2002	1999	2000
Oct	2007	2000	2000	2005	2000	2003	2000	2005	2005
Nov	2002	2006	2004	2004	1999	2007	2004	2003	1999
Dec	2007	1997	1997	2007	2006	2000	2004	1999	2006

Source: AWS Truepower

CHAPTER 7: Conclusions and Recommendations

This report has presented the results of a project designed to improve the understanding and characterization of the wind resources available in promising wind energy development areas of California. These areas included:

- Two focus areas in southern California—Tehachapi Pass and the Imperial Valley region—having significant wind development or expansion potential where greater understanding of the wind resource is desired. A full year of new tower-based wind measurements, complemented by several months of sodar measurements, provides new insights into the wind regime of these areas. The collected data were also used to update California's wind map
- Two additional sites in central and northern California—Kettleman Hills and Snowstorm Mountain—where tower-based time series measurements, previously taken by an Energy Commission contractor (DISGEN), were quality screened and summarized
- Nine community sites where distributed wind applications are under consideration. Time series wind resource data for a typical year were compiled for the selected communities using a map-based modeling approach

Within the two focus areas, wind measurements from two 50 m meteorological towers and a common sodar system were collected between October 2007 and September 2008. These campaigns have supplied valuable data about the temporal characteristics and vertical structure of the wind regimes. Collaboration with two wind developers— Horizon Wind Energy and Iberdrola—was instrumental in identifying high quality wind data sources at representative locations within the focus areas.

The nature and frequency of unusual meteorological events relevant to turbine technologies, plant production and various stakeholders was also characterized. Both areas possess an attractive wind resource that is characterized by relatively low wind shear and turbulence intensity on average, with significant excursions from the means being rare. Occasional high wind speed events are likely, particularly at the Tehachapi site, which can result in plant production losses and additional loads on the wind turbines. Other meteorological events, such as thunderstorms and icing, are very rare in southern California and are thus not expected to impact the wind resource or wind plant production.

In addition to providing detailed wind characteristics information, the measurement campaigns also enabled portions of the California wind map to be updated. Each incremental improvement of the state's wind map provides newer and better information to facilitate the commercial development of wind energy, for both large- and small-scale wind technologies. For this latest project, it was determined that the previous wind map contained modest speed biases in certain areas that have now been corrected. Specifically, the previous Tehachapi Pass portion of the map underestimated the magnitude of the wind resource across the highest wind area, while the Imperial Valley portion underestimated the wind speed change with elevation on the west side of the Imperial Valley. The improved wind map will reduce the uncertainty associated with future project siting and resource estimation within these two focus areas.

This project has also demonstrated that map-based data bases can be used to derive time-of-day wind information that, in turn, can facilitate the assessment of community-scale wind applications where net metering or load matching evaluations are important. As opposed to large scale wind farms, distributed wind system applications are less likely to invest in upfront wind resource measurements, thereby placing greater importance on map-based resource projections.

It is recommended that efforts continue to incrementally expand the understanding of California's complex wind regimes in underdeveloped and undeveloped areas of the State, thereby mitigating the barrier of resource uncertainty that can impair the pace of development for new wind power plants as well as distribution-scale projects. Accurate wind resource assessment is a requirement for the siting and planning of wind projects, and shares an audience of several stakeholder groups. Beneficiaries include wind project developers and owners, as well as O&M providers, turbine manufacturers, and transmission system operators. In addition to project siting, wind resource characteristics also have a direct and indirect bearing on project performance and safety, equipment reliability, economic feasibility, and transmission grid stability. Improved resource assessment techniques, including the use of remote sensing technologies likes sodar and the employment of advanced wind modeling and mapping techniques, can accelerate the site characterization process at a reduced cost and risk.

GLOSSARY

ART	Atmospheric Research & Technology
ASOS	Automated Surface Observing System
AWST	AWS Truepower
DISGEN	Distributed Generation Systems, Inc.
IEC	International Electrotechnical Commission
MCP	Measure Correlated Predict
PST	Pacific Standard Time