Arnold Schwarzenegger
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# California Wind Energy Resource Modeling and Measurement

PIER FINAL PROJECT REPORT

*Prepared For:*
**California Energy Commission**
Public Interest Energy Research Program

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June 2006
CEC-500-2006-062

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# Acknowledgements

The project was sponsored by the California Energy Commission and the U. S. Department of Energy. The report was prepared by Dr. Bruce Bailey and Frank Kreikebaum of AWS Truewind. Contributors include Dr. Michael Brower, Dr. John Zack, Dr. Kathy Moore, Dr. Glenn Van Knowe, Dr. Ken Waight, Michele Weiss, Steve Young, Staci Clark, Mark Taylor, Gary Winslow, Pam Barlow, Dan Bernadett, Pawel Mackiewicz, Rebecca Reed, Jeremy Snyder, Mike Markus and the staff of AWS Truewind.

One sodar system used in the project was leased from Atmospheric Research & Technology; the cooperation of Barry Neil and Bob Zajeski is appreciated.

Hal Romanowitz, Ed Duggan, Frank Pictou, Dave Adams, Sara Pictou, Lupe Castanon, and Alfredo Yttesen of Oak Creek Energy Systems assisted with the Oak Creek tower leasing and installation and made possible the Antelope Valley and Oak Creek sodar sitings.

Thomas Deerfield and the Shasta Energy Group identified and procured the Shasta sodar site and provided technical support.

Scott Quitadamo, Kael Murray and Clear Channel as well as James Ruedlinger of the rest of Electronic Research and Dave Schulgen, Shawn Bachara Lupe Castanon, Brian Bailey, and Norman Ingram of Energy Maintenance Service provided the Rosamond tower lease, setup and decommissioning.

Whitney Washburn, Bill Greep and KXTV arranged for the use of the Transtower tower site. Dave Fields and Field Tower Systems as well as Isaiah Blackmun, Trent McNally, and The Antenna Company enabled the commissioning and decommissioning of the Transtower tower.

Randy Wells and the staff of Maverick Media as well as Doug Dobson of AVTEK provided leasing, commissioning and decommission services for the Geyserville tower site.

David Simkins, John Goglia, Carl Irving and NRG Systems as well as John Campbell and the R.M. Young Company supplied meteorological instrumentation and technical support.

Paula Turner of Desert Pacific Properties and Claude Kirby of the Palm Springs – South Coast Field Office of the Bureau of Land Management assisted with siting of the San Gorgonio sodar.

Kingsley Chen, Bruce Leninger and EcoEnergies, Inc provided tower operations and maintenance services.

The Ukiah Field Office of the Bureau of Land Management, Brian Berndt and Calpine made the Mayacamas Mountains and Calpine sodar sitings possible.

Janice Davis and the Barstow Field Office of the Bureau of Land Management enabled the Mojave sodar siting.

Abstract

This report presents the results of a project designed to improve the accuracy of wind resource estimates through advanced measurement, modeling, and mapping applications in several promising wind development areas of California. Five focus areas were identified: the Mojave Desert, San Gorgonio Pass, Tehachapi Pass/Antelope Valley, the Mayacamas Mountains, and Shasta Valley. For each area, high-resolution wind mapping simulations were run at twice the resolution of the existing statewide wind map, revealing modest adjustments to the intensity and structure of the local wind resource. A campaign of yearlong tall tower wind measurements and short-term sodar measurements was also implemented. These data supplied inputs to a boundary layer modeling research task intended to resolve key simulation problems. A modified statewide wind map was produced. Recommendations are given to expand new measurement and modeling initiatives to other areas of the state having development promise.

## Keywords

Wind map, wind measurement, tall-tower, sodar, boundary layer modeling

# 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 (Commission), annually awards funds to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

What follows is the final report for the *California Wind Energy Resource Modeling and Measurement Project*, Contract Number 500-03-006, conducted by AWS Truewind, LLC. The report is entitled *California Wind Energy Resource Modeling and Measurement*. This project contributes to the Renewable Energy program area.

For more information on the PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/pier/index.html or contract the Commission's Publications Unit at 916-654-5200.

# Executive Summary

This project carried out several recommendations from a previous California Energy Commission (Commission) project entitled “New Wind Energy Resource Maps of California,” Contract #500-01-009. That project developed the current statewide wind map and recommended research that could lead to improvements in the accuracy of the wind map. Three recommended areas of research were: (1) increase the resolution of the model runs in selected focus areas; (2) improve modeling capabilities of the atmospheric boundary layer; and (3) measure the winds at heights relevant to modern turbines, using tall towers and sodar systems, to provide research and validation data for the first two recommendations.

The objective of this project is to improve the accuracy of wind resource estimates in several promising wind development areas of California through advanced measurement, modeling, and mapping. The project consisted of five technical tasks:

- Selection of Focus Areas
- Focused High-Resolution Wind Mapping
- Measurement Program
- Boundary Layer Modeling Research
- Adjustments to the Statewide Wind Maps.

Following a screening process that considered over twenty candidate areas, five focus areas were identified: Mojave Desert, San Gorgonio Pass, Tehachapi Pass/Antelope Valley, the Mayacamas Mountains, and Shasta Valley. High-resolution wind mapping was conducted for the focus areas, with a final mesoscale resolution of 1 km and microscale resolution of 100 m, twice the resolution used to produce the current statewide wind map. The higher resolution model runs revealed that modest adjustments to the statewide wind map are in order within the focus areas because of the improved resolution of influential terrain features. The Measurement Program consisted of one-year of data collection at four tall towers at heights well above industry-standard meteorological masts, plus seven short-term sodar campaigns that measured wind profiles up to heights of 200 m. The boundary layer modeling research identified three key factors affecting simulation accuracy and took steps to better resolve these factors.

The principal benefits of the project to the State of California are:

- Enhanced wind map accuracy within promising wind energy development areas
- New measurement database at modern turbine heights covering 11 sites
- Improved boundary layer modeling and prediction capabilities.

These benefits will help improve the siting of future wind plants, yield more accurate energy production predictions for proposed projects, and enhance the skill of the scheduling and forecasting of next-hour and next-day wind plant outputs for

commissioned projects. It is recommended that other focus areas of the state be investigated through new measurement and modeling initiatives to improve the understanding of their wind regimes. This will broaden wind energy development opportunities in California.

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# 1.0 Introduction

## *1.1 Background and Overview*

In a previous project for the California Energy Commission (Commission) entitled "New Wind Energy Resource Maps of California," Contract #500-01-009, TrueWind Solutions (now AWS Truewind) used its advanced 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. This validation process determined that the mean wind speed estimates were accurate to within a standard error of about 0.4-0.6 m/s, or 6-8%, at a height of 50 m above ground.

Although the new maps and data files represent a major advance over the previous understanding of the State's wind resources, there was room for improvement. A standard error of 6-8% in mean speed implies an uncertainty margin, within 95% confidence, of roughly 20-30% in wind turbine output. In the final report of that project, several issues affecting the accuracy of the wind resource estimates were identified, and the following recommendations for further research were presented:

1) High-resolution modeling of select areas. Certain aspects of California's unusually complex wind regime, such as blocking by coastal mountains and channeling through narrow passes, could not be modeled very accurately at the 2 km grid scale of the MASS model simulations. As tests carried out by AWS Truewind have shown, higher resolution MASS runs could improve the accuracy of the wind resource estimates in promising development areas.

2) Analysis of boundary layer issues. The stability of the nighttime boundary layer has a major impact on the wind resource in certain parts of California, particularly the desert, where it may insulate the surface from high winds aloft. However, it poses a significant modeling challenge that could not be fully explored in the previous project. In-depth research on methods of simulating stable atmospheric conditions could substantially improve the accuracy of the wind maps in such areas.

3) Measuring the wind aloft. Most of the towers that provided data for the validation of the statewide wind map were less than 20 m tall, and lack of knowledge of the wind shear above that height consequently introduced a large uncertainty in the wind resource that would be experienced by modern wind turbines. New measurements using tall towers in promising areas are clearly needed. However, even the current standard 50 m towers do not reach the hub height of

modern wind turbines, which is typically 65-80 m, let alone the tops of their blades which may approach a height of 150 m above ground; and taller towers are expensive. Existing communication towers, however, can offer a relatively inexpensive platform from which to take direct wind measurements at relevant heights in the vicinity of 100 m above ground. New techniques such as sodar can measure the wind to heights of 200 m or more at a moderate cost. In addition to exploring the wind resource at a particular site, sodar could be useful in validating and refining models to simulate the boundary layer, with benefits in other areas being mapped.

4) Land cover data research. The impact of land cover data quality on the accuracy of the initial statewide map was unknown.

## *1.2 Project Objectives*

The objectives of this project are:

1) Generate high-resolution wind resource maps targeting focus areas of complex terrain and meteorology believed to have promising wind development potential; and

2) Provide measured wind data at heights representative at heights above traditional meteorological masts (50 m).

With successful completion of this project, the State will possess one of the highest horizontal grid resolution maps at 200 m with regional refinements at the 100 m level. These refinements are expected to increase the overall accuracy of the maps within the focus areas by 50%. The State will have contributed to improving the accuracy and refinement of the state-of the-art for atmospheric modeling technology, thereby improving the quality of wind mapping and forecasting services available to industry. The project will provide the first publicly available wind measurements using tall towers and complementary sodar technology targeting the 50 m-200 m height interval, which is directly representative of today's large-scale wind turbines.

This project meets the PIER goal of improving the reliability and quality of California's electricity by more accurately defining wind resources in the State and identifying areas of untapped or underdeveloped wind potential. This project also helps to improve energy cost/value of California's electricity by providing better understanding of wind resources and helping to increase market penetration levels through coupling numerical modeling capabilities with meteorological mast monitoring. This project is expected to help increase market penetration by both small and large wind technologies.

## *1.3 Outline of Report Organization*

The report is organized to provide an overview of the entire project. Section 2 summarizes the project approach, which consists of five technical tasks. Section 3 presents the key outcomes of the tasks. Finally, Section 4 discusses the project's conclusions and recommendations and addresses the project's commercialization potential and benefits to California.

During the course of this project, final reports were submitted for each of the major technical work tasks (Task 1 was administrative in nature):

- Final Focus Area Selection Report (Task 2)
- Final Map Draft Comparison Report (Task 3)
- Final Detailed Measurement Program Plan (Task 4)
- Measurement Program Final Report (Task 4)
- Final Boundary Layer Research and Findings Report (Task 5)
- Final Statewide Wind Maps & Modifications Report (Task 6)

With the exception of the Measurement Program Final Report, these reports are included in the appendix of this document and should be consulted to obtain more details about the individual tasks. The Measurement Program Final Report is available as a separate document.

# 2.0 Project Approach

This section summarizes the five main technical tasks (and associated subtasks) comprising the project: (1) Selection of Focus Areas, (2) Focused High Resolution Wind Mapping, (3) Measurement Program, (4) Boundary Layer Modeling Research, and (5) Adjustments to the Statewide Wind Maps.

## *2.1 Selection of Focus Areas*

Selection criteria for the focus areas were defined as:

- The areas should offer significant promise for wind energy development after considering important siting factors;
- Two areas should be within the major, known wind resource areas of the state;
- The remaining three areas should be relatively unexplored and offer the potential for new, large-scale project development;
- The focus areas should represent a variety of terrain in order to adequately test the wind modeling process. One focus area should contain a mountain pass.
- The focus areas should also investigate regions of particular interest to the Commission. One of the areas should be in Northern California; another should be in the Mojave Desert.

It was also desired that tall towers (e.g., communication towers) exist within or near the focus areas so that the meteorological measurements activities of the Measurement Program can be co-located.

A cost-based site screening approach using a geographical information system (GIS) was developed to identify the most cost-effective sites able to support wind project sizes of at least 50 MW. Factors considered include:

- Wind resource as defined by the statewide wind map
- Elevation and air density
- Proximity to transmission
- Proximity to populated areas
- Exclusion of park lands, wilderness areas and conservation areas
- Exclusion of water bodies
- Exclusion of steeply sloped terrain (>15%), which is generally not negotiable by heavy trucks carrying large turbine equipment components.

This approach used capital and construction cost assumptions for wind plants and for roads and transmission lines (including substations), which accounted for distances from existing facilities. Wind plant capacity factors were calculated by matching wind map-derived resource statistics with a generic turbine power curve reflecting current megawatt-scale wind technologies.

From the site-screening results, 22 candidate areas were chose as potential focus areas to satisfy the project selection criteria.

A tall tower search scheme was then applied to the 22 candidate areas to determine those meeting the requirements of the meteorological measurement activities of the Measurement Program. This scheme utilized public datasets as well as information gathered from site visits and in-state contacts.

The results of the above steps were compiled and evaluated, leading to the selection of five final focus areas. The focus areas are named in Section 3.1 and are presented on a map in Figure 1. One focus area is in northern California, another is in the state's central region, and three areas are located in southern California.

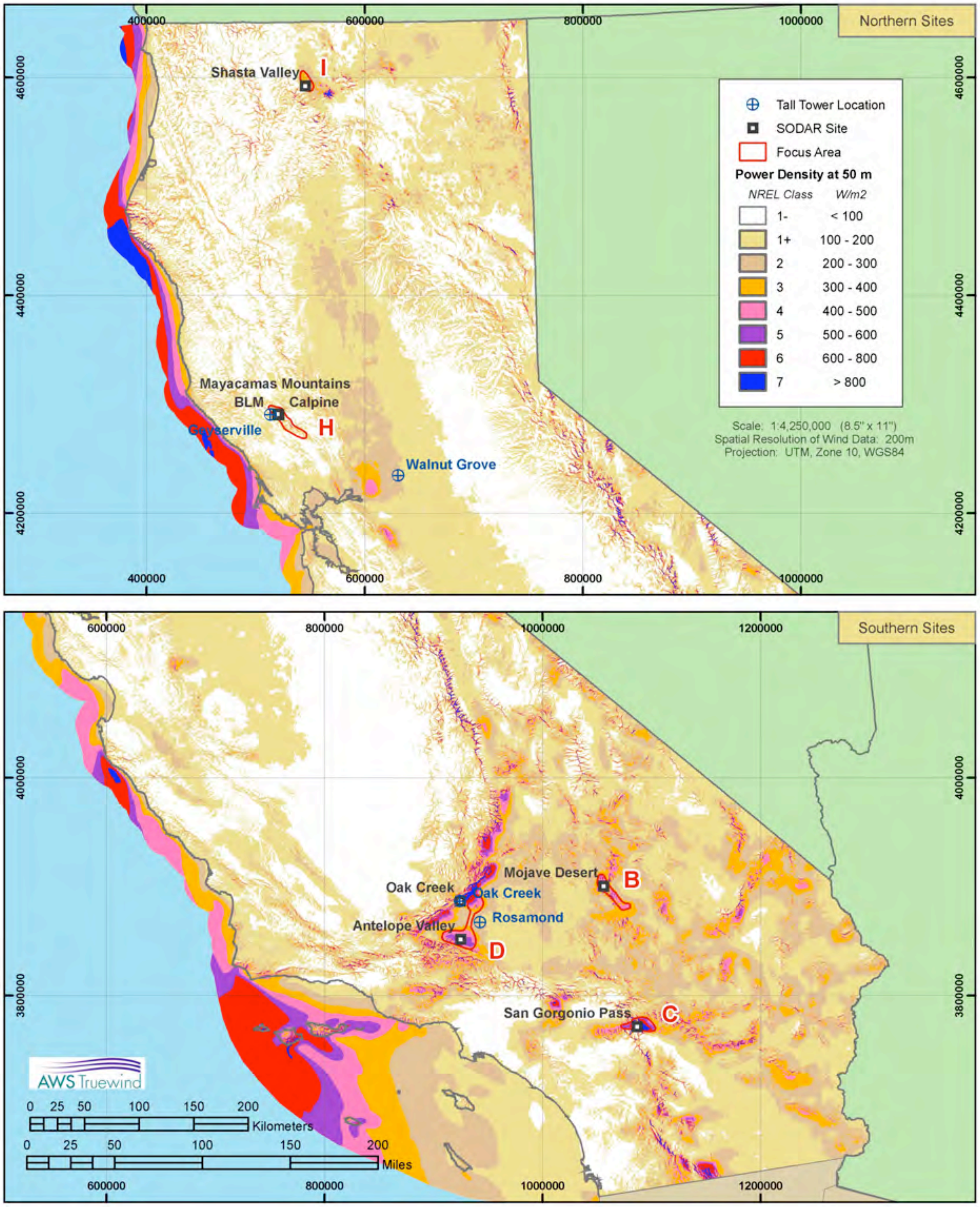


**Figure 1: Overview of Focus Areas as well as Tall Tower and sodar locations Tall Tower and reference station locations**

## *2.2 Focused Wind Mapping*

The wind resources for the five focus areas were remapped using a mesoscale resolution of 1 km and a microscale resolution of 100 m. The maps were compared with the statewide wind maps, which were originally produced in steps of 2 km (mesoscale) and 200 m (microscale) resolution. Where available, the map results were compared with existing meteorological data. However, since this task occurred before completion of the Measurement Program task, data collected during the Measurement Program were compared to the high resolution maps as part of the final task (Section 2.5).

## *2.3 Measurement Program*

A wind measurement program was conducted for the five focus areas. An existing tall tower was used to collect multi-level meteorological data for a full year within three of the five focus areas as well as one candidate focus area (an appropriate tall tower was not available for the fourth and fifth focus areas). Sodar measurements were taken by applying a short-term (up to 5 weeks) campaign strategy at one or two sites within each focus area. The overall measurement period began in April, 2004 and was completed in July, 2005.

A detailed measurement program plan was written to guide the tall tower and sodar campaigns. It specified:

- Site locations
- Measurement period
- Instrumentation preparation, calibration, installation and maintenance protocols
- Data processing and analysis protocols

A summary of this plan is presented as the following two subtasks.

### 2.3.1 Tall Tower Campaign

Tower leases were negotiated with tower owners and tower wind loading studies were performed as needed.

The two towers in central California (Transtower and Geyserville) and two in southern California (Oak Creek and Rosamond) were instrumented at three levels to collect wind speed and direction data. Primary and redundant anemometers and a wind vane were installed at three levels per tower. Pyranometer and temperature sensors were installed at the tower's lowest section. When not impeded by radio frequency interference, calibrated temperature sensors were also installed at the top of the tower to measure thermal stability across the height of the tower, thereby assisting the Boundary Layer Modeling Research task.

At three of the towers, sensors were mounted at a sufficient distance from the tower face to meet the International Energy Association's (IEA) specifications for the instrumentation of tall towers. The one tower not instrumented to IEA specifications (Transtower) had a face width greater than 12 ft. Instrumenting the fourth tower to IEA specifications was not feasible due to budgetary constraints. Tower riggers were contracted to install the equipment, with their work overseen by an AWS Truewind engineer. Equipment maintenance contracts were executed with an in-state firm.

Recorded meteorological data were transmitted via cellular or landline service to AWS Truewind and validated monthly. After a year of recording at each site, the data were analyzed and correlated with regional long-term reference measurement sites (e.g., National Weather Service stations), using the measure-correlate-predict method (MCP), to project the long-term wind speeds. The tower equipment was subsequently decommissioned.

### 2.3.2 Sodar Campaign

Sodar siting permission was acquired from the various landowners of each site (consisting of private individuals, businesses, municipalities, or federal agencies). Two sodar units were deployed simultaneously for the seven-site sodar campaign. The sodar units were transported to each site, set up, and tested by an AWS Truewind engineer. The units were operated at each site for two to five weeks. The units were calibrated before each siting. AWS Truewind or its subcontractors provided scheduled and unscheduled maintenance services. Data were reported via cellular internet connection or manual data retrieval. Data sets were validated and compared to concurrently measured data from the tall towers as well as from nearby reference stations.

## *2.4 Boundary Layer Modeling Research*

The first step was to identify the typical modeling biases and problems. The next step was to identify those problems that were likely related to the boundary layer. The final step was to identify the meteorological cases that were representative of a given boundary layer related problem in order to perform model experiments in an attempt to identify the source of and solutions to the problems.

Two approaches were used to help identify modeling problems relevant to the boundary layer. One approach was an objective statistical analysis of the model output of many cases with observations from various sources to determine where the model was having problems simulating the boundary layer winds. The other approach was a subjective point comparison of model soundings with observed soundings for individual cases. The analysis involved comparing observed wind speed data from sodar, towers, rawinsonde and standard surface weather observations with the model output. There were three categories of modeling problems identified from the field measurements that were most likely related to boundary layer problems.

### *2.5 Adjustments to the Statewide Wind Maps*

The results of the Focused High Resolution Wind Mapping task were reevaluated given the results of the Measurement Program and Boundary Layer Modeling Research tasks. Areas with significantly improved results, verified by measurement, were incorporated into the previous statewide wind map. A new state wind map and accompanying data files were produced and submitted.

# 3.0 Project Outcomes

## *3.1 Selection of Focus Areas*

The five focus areas selected were:

- Mojave Desert (Focus Area B)
- San Gorgonio Pass (Focus Area C)
- Tehachapi Pass and Antelope Valley (Focus Area D)
- Mayacamas Mountains (Focus Area H)
- Shasta Valley (Focus Area I)

The San Gorgonio Pass as well as a portion of the Tehachapi/Antelope area are within well known, developed wind energy regions. They are viable locations for the repowering of current projects and construction of new projects. A variety of terrain types are encompassed within the focus areas, including passes, valleys, and mountain ridges. Shasta Valley is in northern California, and the Mojave Desert area is approximately 120 km east northeast of the Tehachapi Pass. All of the screening criteria developed for this task were fulfilled.

## *3.2 Focused Wind Mapping*

Below is a summary of this task's outcome for each focus area. All task objectives were met.

### 3.2.1 Mojave Desert

The new maps indicate a >10% increase in mean speed in the middle of the area. This enhanced area is in the outflow from a gap between the Calico Mountains and Lane Mountain to the west. This suggests that, at a higher resolution, the model simulates more channeling through the gap. There is a similar but smaller increase in wind speed at the eastern edge of the area at an outflow zone. By contrast, the large area of channeled flow through the Mojave Valley was relatively unaffected by the higher mesoscale resolution, except that it was extended somewhat farther to the east. This indicates that the original mesoscale resolution was sufficient to resolve this pass, but not the other two, smaller passes.

### 3.2.2 San Gorgonio Pass

The new map shows an area of increased speed through the middle of the pass and particularly out the eastern end, and also extending southeast into the Coachella Valley. This was not surprising because of the ability of the mesoscale model to better resolve the pass and its outlet at the higher resolution. Once again, in the mountains, there was a more complex pattern of increases and decreases, with most ridgelines experiencing a moderate increase in the predicted wind speed. A comparison of the original (unadjusted) and new maps with validation data from 18 stations gathered in the first project showed a clear improvement in map accuracy. The adjustments applied to the raw map in the first project were quite similar to the changes resulting from the higher resolution.

### 3.2.3 Tehachapi Pass and Antelope Valley

As with the San Gorgonio Pass, there was a clear pattern of significant increase within and downwind of several passes, most importantly Tehachapi Pass, but also two others, the one to the south known as Cottonwood, and the other to the north, Lone Tree Canyon. The increased wind resource out of Tehachapi Pass extended well out onto the valley floor. Accompanying the increase in the wind resource in the passes, there was a decrease downwind of the higher parts of the Tehachapi Mountains. This was expected, given that, with higher resolution, the MASS model simulates greater blocking of the shallow flow by the mountains, and correspondingly greater flow through the passes. The new map was compared with validation data (25 stations) and an improvement was seen. The original (unadjusted) wind map had very little bias overall (about 0.1 m/s), but the standard deviation between the data and map was 1.15 m/s. With the high-resolution map, the bias remains small (-0.1 m/s), but the standard deviation is reduced to 0.87 m/s.

### 3.2.4 Mayacamas Mountains

The comparison of the new map to the original map presented a rather complicated picture. The average change in mean speed across the whole region was about -6%, i.e., a moderate decrease. This was probably mainly due to increased sheltering of the valleys in the high-resolution simulations. There were a few exceptions – broad valleys which, perhaps because of their orientation to the prevailing wind, were predicted to have a somewhat greater wind resource than in the original wind map. Within the mountains, the impacts of higher resolution were too complicated to be easily interpreted. Most of the variations in the speed ratio were on too small a scale to have anything to do with the mesoscale model. Rather, they reflected small differences in elevation at the microscale. The impact was particularly noticeable on sharp mountain peaks, where slight changes in elevation due to the change in resolution can result in substantial changes in the predicted wind speed. A close examination of the main ridgelines – which are the only areas in the region with a potentially attractive wind resource – reveals a slight decrease in the maximum predicted wind speed. This is to be expected since, at a higher resolution, the mesoscale model was able to simulate more mountain blocking. The impact, however, is quite modest – typically a few percent, or 0.1-0.3 m/s.

### 3.2.5 Shasta Valley

As with the Mayacamas Mountains, the comparison of the new map to the statewide map presented a complicated picture. Focusing on the Shasta Valley, it appears that higher resolution has enhanced the predicted outflow from the mountains, particularly on the west side of the valley.

## *3.3 Measurement Program*

A total of four years of tall tower wind data plus six months of sodar data were collected at the four towers sites and seven sodar sites seen in Figure 1. All objectives of this task were fulfilled.

### 3.3.1 Tall Tower Campaign

Data recovery for the four tower sites was excellent, averaging 96.8%. Except for the Geyserville tower, the highest wind speeds were observed during the late spring and summer months. This was caused by the large continental/marine temperature and pressure gradients that develop during the spring and summer months when the strongest solar heating occurs. Increasing wind speeds between the late morning and mid- to late afternoon hours were observed at all sites. Rosamond was the most strongly affected by the sea breeze because the peak daily winds are observed at around 4 PM before they dropped sharply with the decrease in daytime heating. The other three sites experience nighttime wind speed maxima that were related to boundary layer stabilization and their respective elevations. The wind roses at Oak Creek, Transtower, and Rosamond were all driven by channeling. At Geyserville, the wind direction is more variable than at the other sites due to complex terrain.

The Oak Creek and Transtower sites were both equipped with high-accuracy temperature sensors at two levels to study the effects of stability on the boundary layer wind conditions. Both locations experienced stable conditions during the overnight hours and unstable conditions during the day.

Table 1 summarizes the long-term wind speed projections for the four sites.

Table 1: Tall Tower long-term wind speed projections

| Monitoring Site | Monitoring Height (m) | Wind Speed Projection (m/s) | Mean Wind Shear | 70 m Wind Speed Projection (m/s) | 100 m Wind Speed Projection (m/s) |
|---|---|---|---|---|---|
| Oak Creek | 88.4 | 8.13 | 0.240 | 7.67* | 8.38 |
| Rosamond | 109.7 | 6.89 | 0.240 | 6.16* | 6.74 |
| Transtower | 111.3 | 6.03 | 0.332 | 5.23* | 5.82 |
| Geyserville | 60.1 | 5.90 | 0.087 | 5.98 | 6.17 |

*The 70 m wind speed projection was derived through shear extrapolation from the middle level anemometer because it was closer to 70 m than the top sensor.

### 3.3.2 Sodar Campaign

Sodar availability at the Antelope Valley and Oak Creek sites was 100% and 92% respectively. Comparison of Oak Creek sodar data with Oak Creek tower data resulted in a slope of 0.87 and an intercept of 1.05 m/s, with an $R^2$ of 0.80. The values are not expected to match due to the complex terrain and siting within an active wind farm, resulting in significant wake effects. The 80/50 m shear exponent at Antelope Valley for all periods and for periods with 50 m speeds $\geq$ 5 m/s were both 0.08. Oak Creek 80/50 shear for all periods and for periods with 50 m speeds $\geq$ 5 m/s were 0.23.

Overall sodar availability was 100% and 73% at the Mayacamas and Calpine sites, respectively.

The wind speeds at the Mayacamas and Calpine sodar sites were generally lower than those at the Geyserville tower site. Differences between the sodar and tower speeds were expected given the distance among the sites as well as the extreme terrain complexity. The steep terrain around both sodar sites leads to very low, sometimes even negative, shear. Overall the Mayacamas site had an 80/50 m shear of 0.23 and 0.17 for speeds $\geq$ 5 m/s. Calpine had an overall 80/50 shear of 0.24 and 0.08 for speeds $\geq$5 m/s.

At the Mojave site, the overall availability of the sodar was 60%. All of the data loss was due to a high-temperature shutdown of the power system, which was diagnosed and repaired. The campaign was prolonged to ensure collection of a representative dataset. The overall 80/50 m shear exponent for observations with 50 m speeds $\geq$ 5 m/s was 0.10, and 0.16 for all speeds.

At the San Gorgonio site, the overall availability of the sodar was 99%. The 50/80 m shear exponent was 0.11 for all 50m speeds, and 0.12 for 50 m speeds $\geq$ 5 m/s.

At the Shasta site, the overall availability of the sodar was 98%. The study period was characterized by weak winds punctuated by episodes of strong southeasterly winds. The 80/50 m shear exponent was a low 0.1 for cases where the 50 m wind speed was $\geq$ 5 m/s, and 0.1 for all speed cases as well.

## *3.4 Boundary Layer Research*

Three categories of modeling problems were identified as most likely related to boundary layer problems:

- Atmospheric stability
- Terrain complexity
- Surface energy budget formulation.

All objectives of this task were fulfilled.

### 3.4.1 Atmospheric Stability

Problems related to atmospheric stability generally seem to be the result of the model not being able to resolve or properly handle the energy transfer within the boundary layer during periods when the boundary layer is stable. This problem is most noted during the late evening and early morning hours during periods of clear skies. The surface, rawinsonde, tower and sodar observations all indicate that during these stable periods, there is a tendency of the simulated winds to be higher than observed.

Experiments were run with different mesoscale mode resolutions, types of activated stability regimes, and boundary layer formulations. All three were shown to effect boundary layer problems. In particular, the z-less boundary layer formulation scheme showed particular promise for resolving such problems.

### 3.4.2 Terrain Complexity

Three different factors were tested to improve terrain complexity problems. First, non-hydrostatic model results were compared with hydrostatic results. Cases were discovered where a non-hydrostatic mesoscale model performed better, especially for extreme down slope conditions. But in most cases there was very little difference between the hydrostatic and non-hydrostatic wind speeds. These differences would not be significant when creating a long-term climatology of the wind speeds.

Tests with different models (MASS, OMEGA, and WRF) show little difference between MASS and WRF. OMEGA provided some improvements but underestimated wind speeds and produced unrealistic results. However, the OMEGA model also requires roughly five times more computing runtime as the MASS model and thus does not appear to be advantageous.

### 3.4.3 Surface Energy Budget Formulation

Four types of experiments were performed to improve surface energy budget formulation problems:

- Non-hydrostatic versus hydrostatic experiments
- Resolution experiments
- Sensitivity to mesoscale model used
- Sensitivity to input data surface and atmospheric data

Non-hydrostatic versus hydrostatic, resolution, and model type were not primary factors of surface energy budget problems. However, input data had a significant impact. In particular, the availability of both rawinsonde and surface data improve model performance. More significant improvements were noted with the use of:

- Updated soil moisture data, accounting for newly irrigated lands in the Coachella Valley
- More accurate sea surface temperature data, which also included larger inland water bodies (such as the Salton Sea).

## *3.5 Adjustments to the Statewide Wind Maps*

Not enough data were available in the Mayacamas Mountains, Mojave, and Shasta Valley focus areas to determine if the higher resolution maps were a significant improvement over the statewide map. Therefore, no adjustments were made to the statewide maps in these areas.

In the San Gorgonio area, the changes resulting from the higher resolution simulations were similar to the manual adjustments that were made to the original maps during the validation. For this reason, no further adjustments were required in this area.

In Tehachapi Pass, the spatial pattern of changes due to higher resolution modeling was quite different from the manual adjustments. Moreover the combination of the manual adjustments and higher resolution produced a more accurate map than either alone. Therefore, the higher resolution Tehachapi map was incorporated into the adjusted statewide wind map. See Figure 2 and Figure 3.

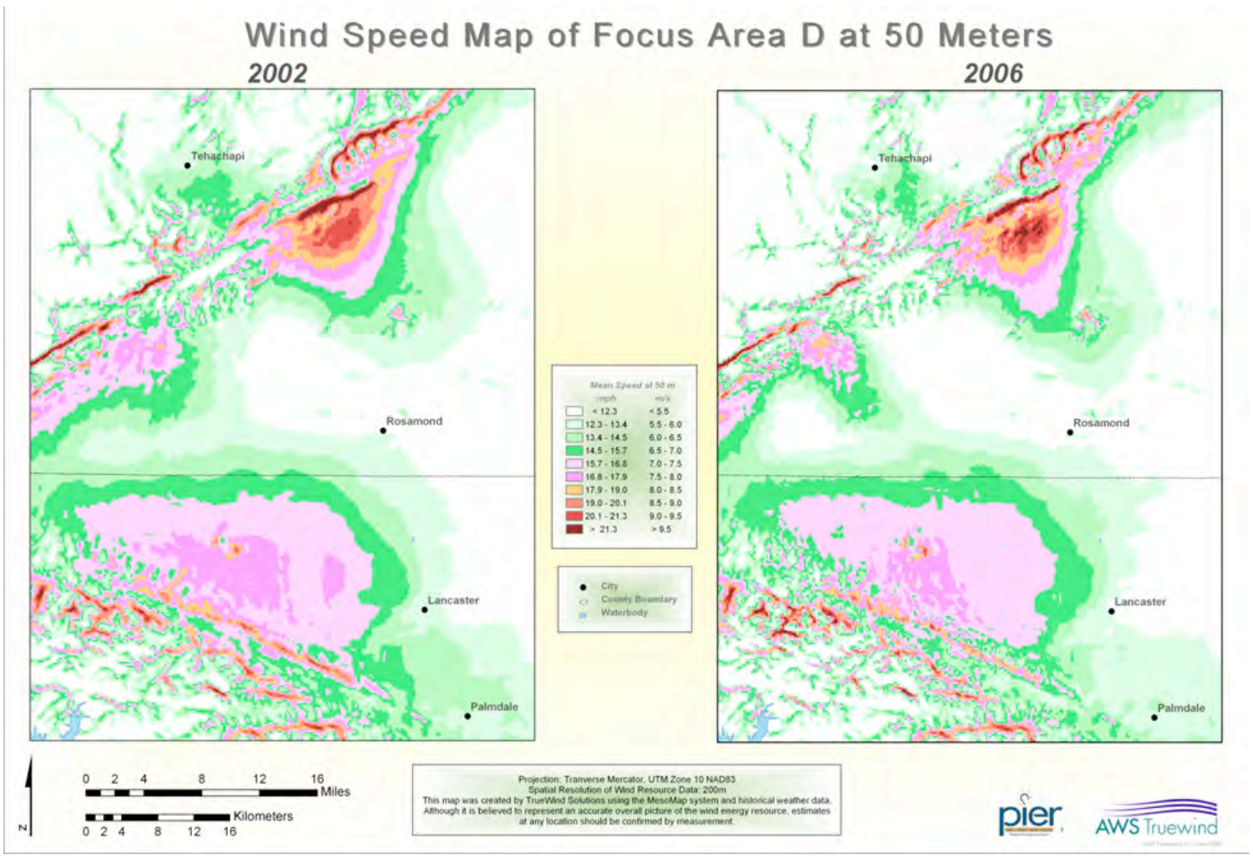


**Figure 2: Comparison of 2002 and 2006 wind speed maps for Focus Area D**

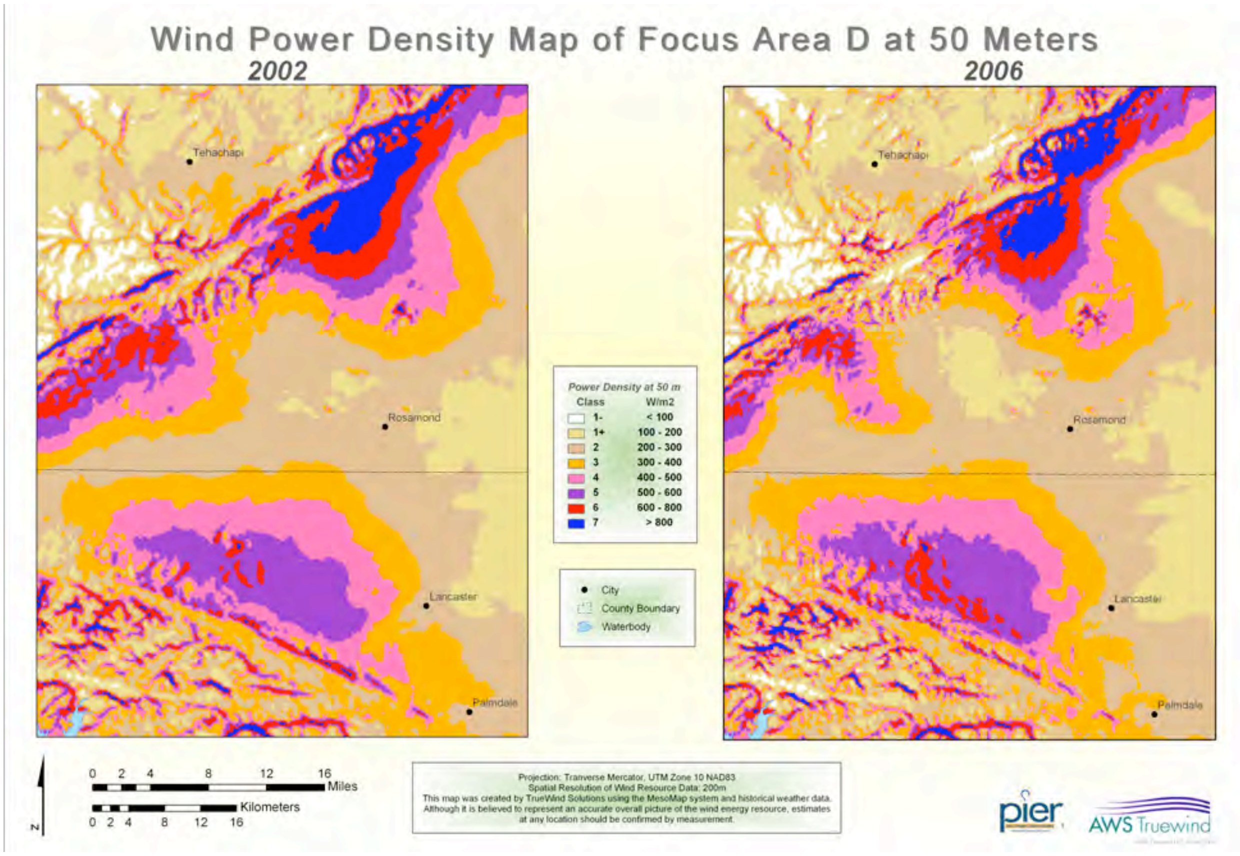


**Figure 3: Comparison of 2002 and 2006 wind power density maps for Focus Area D**

The Boundary Layer Modeling Research task determined that the accuracy of the mesoscale simulations could be improved by implementing a “z-less” boundary layer formulation as well as a new soil moisture database, which takes into account irrigation, and a new sea-surface temperature database. However, it would not be possible to apply a systematic correction to the statewide wind resource maps to reflect these changes without running the modified mesoscale model for the full sample of 366 days. The new map would then have to be validated again and possibly adjusted to address any remaining errors.   This work fell outside the budget of this project.  All objectives of this task were fulfilled.

# 4.0 Conclusions and Recommendations

## *4.1 Conclusions*

This report has presented the results of a project designed to improve the understanding and characterization of the wind resources available in several promising wind energy development areas of California. The five selected focus areas represent a cross-section of meteorological and terrain types within different geographical areas of the state. Knowledge of the wind resources within these areas was improved through the application of advanced measurement, modeling, and mapping techniques.

The higher resolution modeling of the wind resource in the focus areas revealed more structure to the wind flow, as expected. In areas where mountain blocking and channeling are important, the new simulations increased the blocking effect and produced stronger flows through the passes. In other areas, the high-resolution runs produced more sheltering of the valleys by mountain peaks. Katabatic flows out of the mountains into valleys in northern California were moderately increased at the higher resolution. In two focus areas – San Gorgonio and Tehachapi – where enough data was available to validate the maps, the high-resolution runs produced a definite improvement in accuracy.

This project collected the first publicly available wind measurements using tall towers and complementary sodar technology targeting the 50 m - 200 m height interval, which is directly representative of today's large-scale wind turbines. A lesson learned during the screening process to select towers was that inordinate delays can occur when negotiating tower use agreements (and associated engineering studies) with the tower owners. The measurement program data enabled the boundary layer modeling research component but more data would have allowed for more comprehensive research and map validation in three of the focus areas (Mayacamas Mountains, Mojave, and Shasta).

The tower and sodar data enabled model versus observation comparisons that led to the identification of several modeling problems. The data also helped to determine the cause, and in some cases, the solution to the various problems. Boundary layer characterization can be improved by better accounting for atmospheric stability, terrain complexity, and surface energy budget formulation. Increased model resolution, use of the z-less scheme, and incorporation of better surface data (namely soil moisture and sea surface temperature) have the most beneficial impacts. Modeling in non-hydrostatic mode, the use of different mesoscale modes, the use of higher resolution initial condition data, or changing the stability scheme, offered little to no improvement.

The higher resolution map simulations in the Tehachapi area have been merged seamlessly into the statewide wind resource maps. The result is a somewhat greater concentration of the wind resource in a narrower band south of the Tehachapi Pass and Cottonwood Pass. The changes elsewhere are modest.

## *4.2 Commercialization Potential*

Accurate wind resource assessment is a requirement for the siting and planning of a wind power plant. Improved resource assessment techniques, including wind mapping, can accelerate the site identification process at a reduced cost. Whereas previous development activity required one or more iterations of on-site wind assessment using meteorological masts to locate the best sites of interest, wind mapping allows project developers and government agencies to identify promising sites with greater certainty. Relatively small areas that may have gone unnoticed in the past are now also revealed through high-resolution mapping.

Wind mapping began in California decades ago with regional maps and the NREL National Wind Atlas. With the advent of new computer technologies and meteorological models, the wind map created by AWS Truewind under Contract #500-01-009 improved upon these initial products. This project represents an improvement over the statewide wind map released four years ago. Each step of the process has provided newer and better information to facilitate the commercial development of wind energy, for both large- and small-scale wind technologies.

This project addressed the PIER goal of improving the reliability and quality of California's electricity by more accurately defining wind resources in the State and identifying areas of untapped or underdeveloped wind potential. This project also helped to improve energy cost/value of California's electricity by providing better understanding of wind resources and helping to increase market penetration levels through the coupling of numerical modeling with advanced field measurements.

## *4.3 Recommendations*

While atmospheric modeling techniques continue to improve, high-quality validation from on-site data continues to be essential. Therefore, additional field measurements are recommended, especially in non-developed areas of great potential such as the Mojave, the region northeast of the Tehachapi, and areas along the California – Mexican border. While the Mojave was selected as a focus area and other regions were identified in this project as candidate focus areas, the scope of this project did not provide for comprehensive data collection in most of the promising areas of future development. In particular, while a short-term sodar campaign was conducted in the Mojave, the area lacked a meteorological mast at or near hub-height mast with at least of year long period of record. A cost-effective approach to data collection in such areas would be the installation of industry-standard meteorological masts (50-60 m) at targeted locations within each area coupled with short-term sodar campaigns to characterize the shear and vertical velocity up to 200 m above ground.

In tandem with new measurement campaigns, the running of higher resolution atmospheric models with upgraded input databases (e.g., soil moisture, sea-surface temperature, etc.) will yield improved siting information in the form of advanced wind maps. These maps can be produced most cost-effectively when run for targeted focus areas and then blended into the master statewide wind map.

### *7.4 Benefits to California*

This project encourages the development of wind energy in the State by helping companies and individuals identify promising wind project sites with enhanced accuracy compared with previously available information. This not only benefits individual project development, but medium- and long-term planning activities such as transmission upgrades, land-use reclassifications, and changes in statewide, regional and local permitting requirements benefit as well. The high-quality data collected from the several sites at heights above traditional meteorological masts will enable government agencies, companies and individuals to reduce the uncertainty of development in those focus areas. Finally, improved boundary layer modeling techniques provide more efficient plant siting as well as more accurate energy production predictions for proposed projects and production forecasting for commissioned projects.

# Appendix

I Final Focus Area Selection Report
II Final Map Draft Comparison Report
III Final Detailed Measurement Program Plan
IV Final Boundary Layer Research and Findings Report
V Final Statewide Wind Maps and Modifications Report

# I

# Final Focus Area Selection Report

# II

# Final Map Draft Comparison Report

# III

# Final Detailed Measurement Program Plan

# IV

# Final Boundary Layer Research and Findings Report

# V

# Final Statewide Wind Maps and Modifications Report