

# Atmospheric Boundary Layer Wind Tunnel Applications in Wind Turbine Siting

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## Abstract

*Atmospheric boundary layer wind tunnels (ABLWTs) have been used for 40 years to simulate the interaction of the wind and earth in the lowest few hundred meters of the atmosphere. ABLWTs are well-suited for investigating flow in complex terrain and have different strengths and weaknesses than numerical modeling. There are a wide variety of applications, including performing wind resource assessments of potential wind farms in complex terrain by surveying the flow near the surface. Several examples of wind energy related studies carried out in the University of California, Davis (UCD) ABLWT are presented.*

*KEYWORDS: wind-tunnel, resource assessment, atmospheric boundary layer, complex terrain.*

## Background

Most modeling of wind farm sites for resource assessment purposes is done using numerical computer simulations of the flow over the terrain in and near the wind farm. There are several difficulties involved in implementing these models, with perhaps the most significant being the difficulty of accurately representing the complex terrain surface in a discrete grid, and ensuring proper turbulence closure in the flow. If strict similitude modeling rules are followed with experiment design, an ABLWT simulation is inherently of high resolution, and since the atmosphere is being modeled using air and the "turbulence" used in the physical simulation is physically generated and similar to that used in the atmosphere. ABLWTs are used for a variety of investigations, including determining wind loads on buildings, street level winds in urban environments and dispersion of exhaust gases from smoke stacks for air quality assessment.

A high resolution model can be placed in the ABLWT that includes topographical features such as buildings, small hills or valleys, and sharp or steep ridgelines. The ABLWT is specifically designed to produce a fully turbulent flow field including several decades of the turbulent cascade, that is directly scalable to the terrain and wind conditions being modeled. The limitations of the ABLWT include that only neutrally stable conditions can be simulated, Coriolis force is not included so only measurements within a few hundred meters of the surface are generally valid, and the size of the area that may be modeled is limited by the size of the tunnel test section. Numerical simulation of the same topography generally includes the Coriolis force, and can accommodate larger regions. However, near the surface, correct simulation generally requires a computationally intensive high resolution grid, and correct simulation of turbulence is difficult. Significantly, the primary limitations of the ABLWT are different from the primary limitations of computer simulation, and the combined use of both methods can therefore be expected to yield additional insights in resource assessment.

## UC Davis Atmospheric Boundary Layer Wind Tunnel

The UC Davis Atmospheric Boundary Layer Wind Tunnel (UCD ABLWT) is designed for simulating neutral atmospheric boundary layer flows past surface objects. It is an open-return type tunnel, as seen in Fig. 1, composed of five sections: an entrance section, a flow development section, a test section, a diffuser section and a 56 kW (75 hp) DC motor and fan. Wind speeds within the tunnel can be varied from 1 to 10 m/s (2 to 22 mph). A bell-shaped entrance section provides a small contraction area ratio. An air filter, to screen out airborne particles and reduce any large-scale pressure fluctuations, is followed immediately by a honeycomb flow straightener and a series of spires to "pre-form" the boundary layer.

A 12 m (39 ft) long flow development section is used to generate a mature boundary layer at the test section. An adjustable ceiling and diverging walls in the development section maintain a zero-pressure-gradient flow. Roughness elements are placed on the floor of this section to generate the proper boundary layer height in the test section. The test section is 3.7 m (12 ft) long, 1.7 m (5.5 ft) high and 1.2 m (4 ft) wide. Plexiglas® windows on each side allow observation, and a sealed, sliding door is used for access. Measurements are made using a three-dimensional traversing probe system that is mounted to the ceiling of the test section. This system allows

for precise placement of a sensor at any point within the test section. Small 1 mW lasers are mounted on the traverser to sight vertical height and horizontal position to within 1 mm.

Mean velocity and turbulence intensity are measured using single wire, end flow hotwires (TSI Model 1210-20). The hotwire is supported on the end of a straight 50 cm probe, which in turn is secured to the internal three-dimensional traversing system in the test section of the ABLWT. The traversing system allows the probe to be positioned anywhere within the boundary layer in the test section. The hotwire is electrically connected via a 10 m shielded tri-axial cable to a constant temperature thermal-anemometry unit with a signal conditioner, TSI Model IFA 100. The analog signal from the signal conditioner is passed to a 12-bit analog to digital (A/D) converter and then to a computer for analysis and data storage by a National Instruments LabView program. Thermal anemometry has been widely used in measuring turbulent characteristics for its ability to sample flow velocity at frequencies up to or exceeding 1000 Hz. Typically, hotwire measurements made close to the surface have an uncertainty of less than  $\pm 5\%$  of the true values.

Additional instrumentation can be used to extend the capabilities of the ABLWT. Gas dispersion, such as from an exhaust stack, can be investigated by injecting a tracer gas at the simulated stack. The dispersion of the smoke can then be surveyed by affixing a sampling tube to the traverser and taking samples at different locations. By analyzing the air samples using a hydrocarbon analyzer, the relative dilution of the effluent can be determined. Flow visualization also can be performed by injecting smoke or neutrally-buoyant helium filled bubbles into the flow.

## Wind-tunnel Simulation of the Atmospheric Boundary Layer

The boundary layer within the wind tunnel simulates the same turbulent characteristics found in the full-scale atmospheric boundary-layer. It is important that the atmospheric boundary-layer approaching the modeled region have the same characteristics as it does in full-scale. Otherwise, the changes in local velocity over the model will not be accurately simulated. The relationship between the mean velocity  $U$ , and height above the surface  $z$ , for a boundary-layer of height  $\delta$  and a mean velocity of  $U_\infty$  at height  $\delta$ , is described by the power law:

$$\frac{U}{U_\infty} = \left( \frac{z}{\delta} \right)^\alpha \quad (1)$$

The power-law exponent  $\alpha$  defines the shape of the boundary layer velocity profile. Its value in the wind-tunnel must closely match the full-scale value of  $\alpha$ . Generally, the value of  $\alpha$  depends on the terrain roughness. Over a large city,  $\alpha \approx 0.35$ , while over open ocean  $\alpha \approx 0.1$ . This range of  $\alpha$  can be achieved in the ABLWT by placing different arrangements of “roughness elements” over the floor of the development section. For example,  $\alpha = 0.19$  can be achieved in the UC Davis ABLWT by systematically arranging a pattern of 8.9 x 14.6 x 1.9 cm (thin blocks) and 8.3 x 19.7 x 3.8 cm (thick blocks) wooden blocks over the entire flow-development section of the wind tunnel. The block pattern roughly consisted of half of each type of block configured in alternating sets of four and five blocks per row. A typical mean velocity profile produced by this arrangement is shown in Fig. 2.

In addition, the approaching mean velocity profile should also agree with the logarithmic, or “law-of-the-wall,” wind profile, within the lower region of the boundary layer:

$$\frac{U}{U_*} = \frac{1}{\kappa} \ln \left( \frac{z}{z_0} \right) \quad (2)$$

where  $\kappa$  is von Kármán constant ( $\approx 0.42$ ). The surface layer, the lower 10 to 15% of the atmospheric boundary layer, is governed by Eq. (2). For proper wind-tunnel modeling, the model must be geometrically scaled to remain within this bound. Another parameter that must be considered is the surface roughness Reynolds number  $Re_z = U_* z_0 / \nu$ , where  $U_*$  is the friction velocity,  $z_0$  is the surface roughness and  $\nu$  is the kinematic viscosity of air. Proper simulation of a turbulent boundary layer flow requires  $Re_z > 2.5$ . This is achieved by ensuring that smooth surfaces are kept to a minimum. For the ABLWT, a free-stream velocity of  $U_\infty = 3.1$  m/s, friction velocity  $u_* = 0.22$  m/s, and roughness height  $z_0 = 0.00095$  m, gives  $Re_z \approx 14$ , indicating the simulated atmospheric flow is aerodynamically “rough” and similar to full-scale conditions.

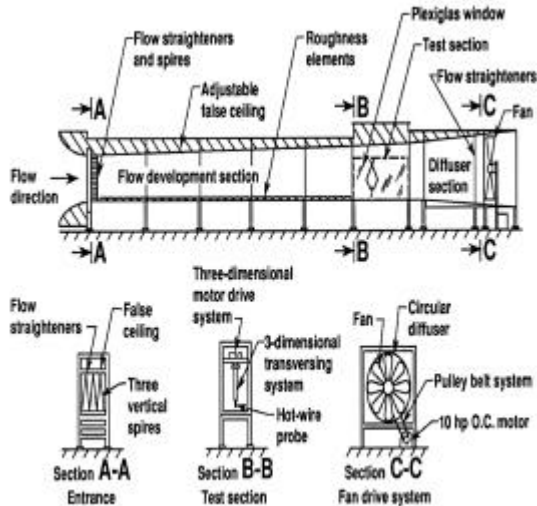


Fig. 1. Schematic diagram of the UC Davis Atmospheric Boundary Layer Wind Tunnel.

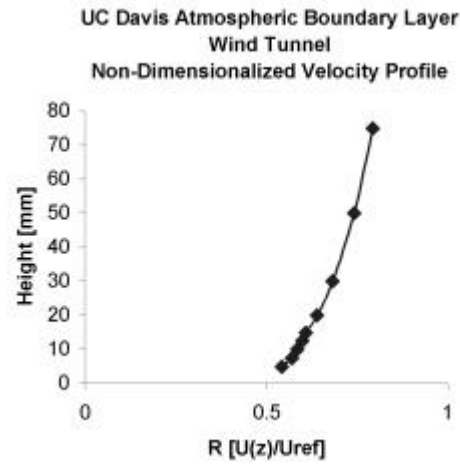


Fig. 2. Typical velocity profile in UC Davis Atmospheric Boundary Layer Wind Tunnel.

## Wind Energy Applications

### Wind Resource Assessment

Several studies have been carried out in the UCD ABLWT demonstrating that wind tunnel simulation of the terrain of a wind farm can be used to determine the mean wind speed and turbulence intensity at current or potential wind turbine sites, even if the site is in complex terrain. If the turbines are spaced sufficiently far apart along the primary wind direction, it is not necessary to model to wakes of the turbines themselves, however, the flow field at turbine height over the site must still be determined.

The first wind energy related study in the UCD ABLWT was a wind resource assessment for a proposed wind farm site in the Pacheco Pass, California, USA in 1985 [1]. This study consisted of the construction of a model of a potential wind farm site, surveying the wind distribution in the wind-tunnel and comparing to the few available field measurements. Although this was a small study, it was one of the first wind-tunnel simulations to be performed specifically for wind resource assessment.

A study of a potential wind farm site on steep terrain near the southern coast of Crete demonstrated good agreement with field data, especially in the prediction of peak wind speeds and turbulence intensity [2]. The site experiences power generating winds predominately from the north and south. A model was built of the terrain and the flow was sampled at points throughout the site, with the model oriented to simulate north, and then south, winds. The wind tunnel predictions were also compared with predictions from an early version of WAsP, and it was observed that while the wind-tunnel predictions varied slightly from the WAsP predictions, the results of both were complimentary (Figs. 3, 4, 5). For example, a high wind area in the farm site, confirmed by field measurements, was not fully identified by WAsP, probably due to the high wind area being downwind of other high regions. However, the WAsP results also identified several sites of interest due to its ability to integrate wind from all directions, whereas the wind tunnel test was limited to using data from north or south. The ABLWT also was used to investigate the correlation between the flow field at different locations over the site in order to select locations to install meteorological towers that would be expected to experience the most representative winds on the site [3].

A recent series of studies of an existing wind farm in the Altamont Pass, California, USA showed that the wind tunnel could be used to develop a wind farm power curve as a function of wind speed and direction measured at the farm meteorological tower [4,5]. Since the area surveyed was an existing wind farm, it was possible to directly evaluate the accuracy of the wind farm power curve by using measured wind speed and direction at the wind farm meteorological tower as input data, and comparing the resulting power prediction with the actual power produced.

The Altamont Pass wind farm consists of approximately 100 100 kW turbines positioned in rows along several adjacent ridgelines, with hub heights at about 20 m. A meteorological tower is located with the turbines on one of the ridgelines. Power producing winds blow most commonly from the west southwest. The terrain at the Altamont Pass wind farm site was modeled in polystyrene foam at a scale of 1:2400, using 2.5 mm steps, or "terraces" to simulate the terrain (Fig. 6). This was done to ensure surface roughness over the model. The model

of the terrain covering all of the turbine sites fit on a panel 1.2 m square that fully spanned the ABLWT test section (Fig. 7). The terrain was modeled on the square panel so that, depending on how it was placed in the ABLWT, winds from 60°, 150°, 240° or 330° could be simulated. Four additional square terrain panels were constructed, so that one fit adjacent to each side of the central panel. To test one of the four wind directions, the three appropriate panels would be placed in the wind tunnel, accordingly, several kilometers both upwind and downwind of the wind farm would be included in the modeled region.

For each of the four wind directions, the wind-tunnel test consisted of measuring the mean wind speed at simulated hub height at each of the turbine locations. This data was normalized by the mean wind speed measured at simulated anemometer height at the location of the wind farm meteorological tower. The data for each of the four measured wind directions was then interpolated to construct a database of normalized turbine wind speeds for winds from any direction. This database allowed the wind speed at each of the turbine locations to be predicted if the wind speed and direction at the meteorological tower was known. Knowing this information, the power production of an individual turbine can be predicted by applying the wind speed at the turbine to the turbine manufacturer's power curve. Summing the power for all the turbines then gives a prediction for the wind farm power production, assuming 100% turbine availability.

For the Altamont Pass site, it was determined that using the wind farm meteorological tower wind speed and direction, and applying the wind tunnel measurements and the wind turbine's manufacturer's power curve, the power production could be predicted with a mean absolute error of 6% of the wind farm's observed capacity. A one week comparison between the wind tunnel prediction and the actual power produced is given in Fig. 8. For the one year period from July 1, 2003 to June 30, 2004, the wind-tunnel method predicted a total power production of 104% of the actual total power production. Significantly, these results were obtained without any "tuning" of the method, so that the same method could be used to simulate a proposed wind farm, with the same expected accuracy.

It should also be noted that the Altamont Pass is a difficult wind resource region to model. The region consists of multiple series of ridgelines, almost all of which have turbines installed, and the wake effects of upwind topography can be pronounced, especially for the smaller turbines modeled here. Also, the strongest winds generally occur at night, and are associated with moderate atmospheric stability, while the ABLWT models neutral atmospheric conditions. Confirming this, comparison of data from a second meteorological tower in the modeled region showed that the wind tunnel gave the best predictions at times of day and seasons when neutral or unstable conditions would be expected, and was least accurate when high stability would be more likely to occur [4].

## Wind Turbine Wake Modelling

The ABLWT also can be used to study very localized effects, such as the effect of wind turbine wakes on downwind turbines. A recent review of wind turbine wake research is given by Vermeer et al. [6]. The key challenge in wind-tunnel simulation of wakes is to determine a model that will generate a wake that correctly simulates the variations in velocity deficit and increased turbulence found downwind of an operating wind turbine. The interaction of wakes in large arrays of regularly spaced turbines has been investigated in ABLWTs using "static simulators," small models generally consisting of a semi-porous disk or vane anemometer, chosen so that the velocity deficit and turbulence intensity produced by the models match those in full scale [7,8,9]. Taylor and Smith [10] simulated a turbine placed upwind of a hill, and found that the hill caused significant changes in the wake properties. Neff et al. [11] simulated up to five turbines in an ABLWT using dynamic models. The 1:50 scale models were functional turbines that included moving rotors driving small generators to extract energy from the flow. There were a number of complications in this approach. The generators needed for the models were too large to fit in the model nacelle, and so belt drives were used to place the generators below ground level. Achieving power similarity required different rotor blade geometry than used on the full-scale turbine, and finding the best model rotor was a prolonged, iterative process.

For the purposes of determining wake effects in complex terrain, the individual turbines must be modeled at a small enough scale to allow the surrounding terrain to be included. It must also be possible to include multiple turbines on the model, limiting both the complexity of the models and their overall size. Therefore, the simpler approach of modeling the rotor using a porous disk was recently revisited at UCD, with the understanding that the simulation would only be valid in the far wake (more than ~2 rotor diameters behind the turbine) region. An example of the mean wind velocities observed behind one such model ( $D = 6$  cm diameter disk with 50% porosity, 10 cm to simulated hub height) for different distances  $L$  downwind is given in Fig. 9. To simulate a specific full size turbine, the velocity deficit (i.e., the amount of momentum removed from the flow by the turbine) required would be dictated by the thrust and power coefficients of the operating turbine, while the required turbulence intensity would be determined based on field measurements or empirical or theoretical predictions.

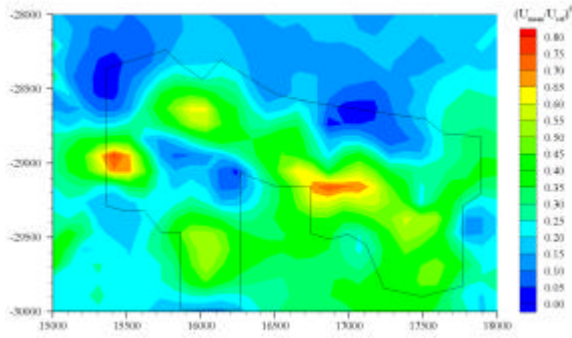


Fig. 3. Wind energy distribution for south wind at 40 m height (full-scale) in the wind tunnel.

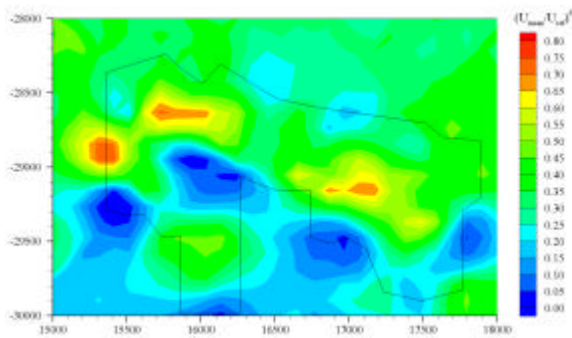


Fig. 4. Wind energy distribution for north wind at 40 m height (full-scale) in the wind tunnel.

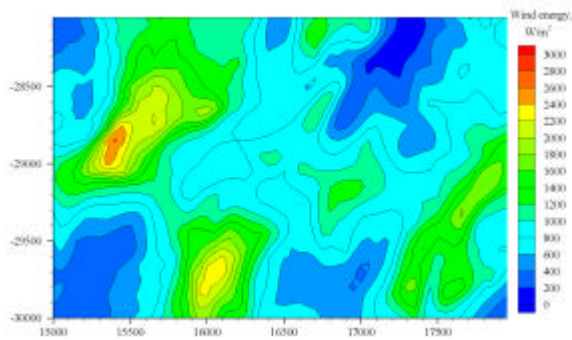


Fig. 5. Wind energy distribution based on the WASP program results for 40 m above ground level.

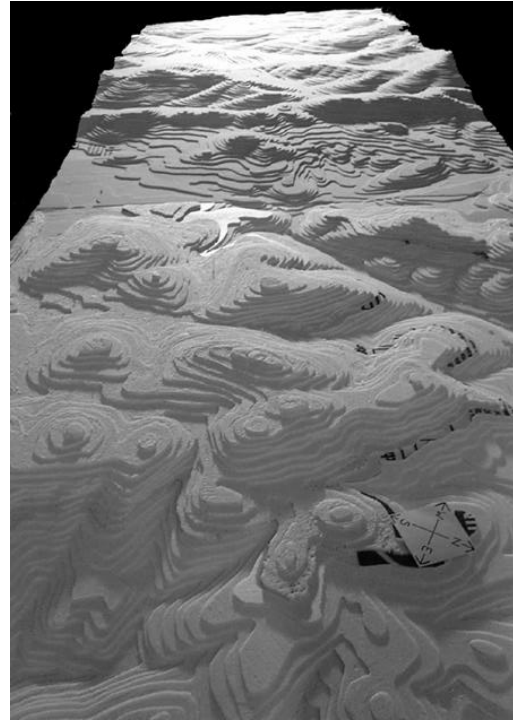


Fig. 6. Model of Altamont Pass wind farm for 240° wind. Turbines are on ridges of middle panel.

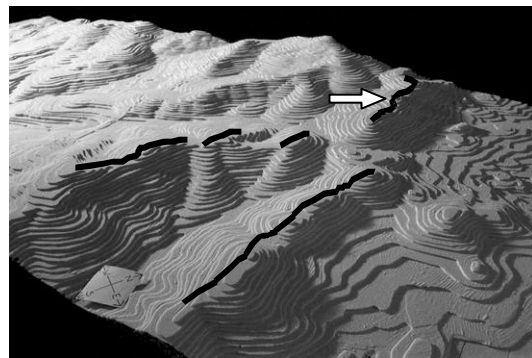


Fig. 7. Altamont turbine sites marked by black lines. Arrow indicates meteorological tower location.

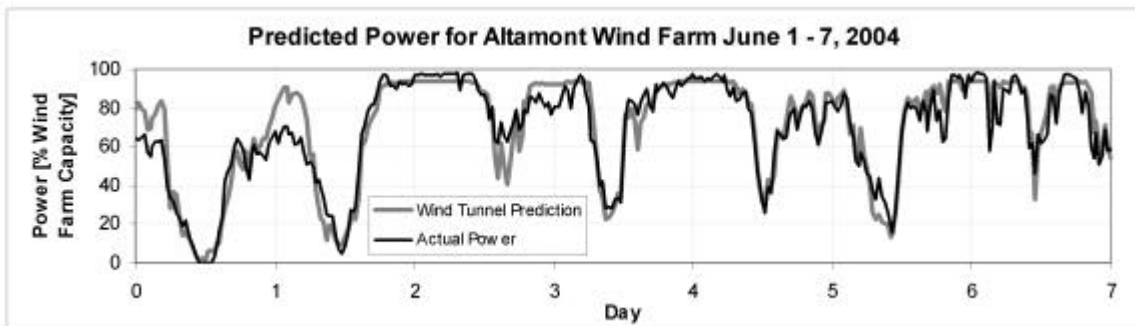


Fig. 8. Example of power prediction using wind tunnel methods with wind speed and direction measured at wind farm meteorological tower as input, compared to actual power production, for Altamont Pass wind farm. July 1-7, 2004.

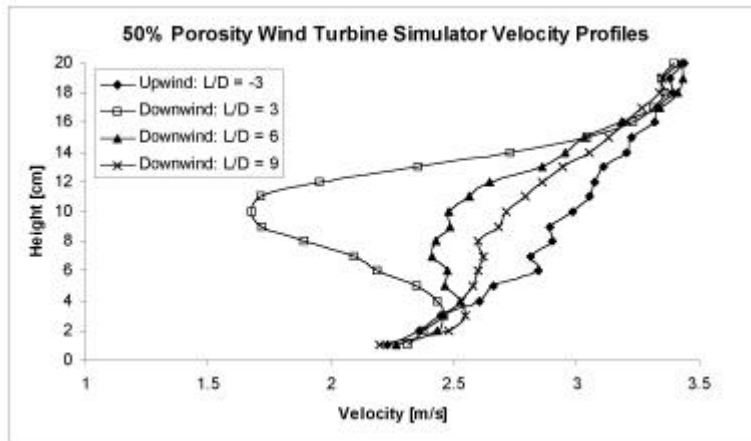


Fig. 9. Velocity profiles from UCD ABLWT test of 50% porosity static wind turbine simulator of diameter  $D = 6$  cm, for different distances  $L$  downwind.

## Conclusions

The ability of atmospheric boundary layer wind tunnels (ABLWTs) to simulate turbulent flow over complex terrain can be utilized for wind resource assessment and wind turbine siting purposes. Since the limitations of the wind-tunnel simulation are generally different than the limitations of numerical models, the use of both methods is advised in difficult turbine siting problems.

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