Wind Resource Assessment Handbook

Final Report 10-30
October 2010

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Energy Research and
Development Authority

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WIND RESOURCE ASSESSMENT HANDBOOK

Final Report

Prepared for the

NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

Albany, NY
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NOTICE

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ABSTRACT AND KEY WORDS

The wind resource assessment campaign represents one of the most important phases in the development of utility-scale wind farms. The energy production estimates that are generated based upon the results of the wind measurement campaign are essential in determining the feasibility of a proposed wind farm project. This handbook presents industry-accepted guidelines for planning and conducting a wind resource assessment program. Included is a comprehensive overview of the wind monitoring process, which involves the siting, installation, and operation of a meteorological towers, as well as advanced remote sensing technologies. Recommended best practices for the subsequent data collection and validation are provided. Advancing beyond the initial wind monitoring and data collection phases, a detailed discussion of the analytical methods involved with estimating a site's wind energy potential is presented. These analyses include extrapolating observed wind measurements to hub height, adjusting the measured data to the long-term historical norm, wind flow modeling, and the assessing the uncertainty associated with resulting energy production estimates. This handbook will provide the assessor with detailed understanding of the wind resource assessment process, as well as the analyses involved with the estimating wind farm energy production.

KEY WORDS: wind resource assessment, wind data, wind farm, wind energy, meteorological tower, anemometer, wind vane, remote sensing, lidar, sodar, AWS Truepower.

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SUMMARY

The development of modern utility-scale wind farms often requires that the developer conduct a wind resource assessment campaign prior to construction. The information that is collected during this measurement program is utilized to estimate the potential energy production from a proposed wind farm project, thereby providing information to help determine the economic viability of installing a wind farm at a given location. These estimates of energy production are typically used by the developer to secure funding for the project. Consequently, one of the primary goals of the measurement campaign is to reduce the uncertainty associated with the energy estimates, which helps to reduce the risk perceived by the investor. This handbook provides guidelines for planning and conducting a wind resource measurement program to support the development of utility-scale wind farms.

Wind resource measurement campaigns involve the use of equipment such as meteorological towers instrumented with anemometers, wind vanes, and temperature sensors. Alternatively, remote sensing devices, which emit either sound pulses (sodar) or lasers (lidar) to measure the wind, are gaining acceptance within the industry and will likely play an increasing roll in future wind resource assessment efforts. This equipment can measure and record weather information (e.g., wind speed, wind direction, gusts, temperature) that is used, along with long-term meteorological reference data, to characterize the long-term wind resource at the site. The proper design of a wind resource assessment campaign is critical to obtain the best possible understanding of the wind resource across the project area. Factors such as the location and height of meteorological towers, instrumentation configuration, and maintenance procedures, among others, can have a significant influence on the results of the measurement campaign. It is recommended that all of the information pertinent to the measurement program (e.g. measurement parameters, QC protocols, maintenance schedule, etc.) be outlined in a comprehensive measurement plan.

After the measurements are recorded by the wind sensors, these data are then typically remotely transmitted to a repository where they are archived and validated for further analysis. During the validation process, the data record is evaluated and screened for suspect or potentially erroneous values. One element of the analysis process deals with adjusting the wind measurements to turbine hub height. If the wind measurements were taken at a height below the anticipated hub height of the project's wind turbines, which typically ranges from 80 to 100 meters for most modern turbines, the measurements are then extrapolated up to hub height through an intricate process that is dependent upon a number of factors. One of the final steps in the analysis involves the adjustment of the observed wind measurements to the historical norm for the site; this adjustment is necessary due to the variable nature of the wind. By using a process known as "measure, correlate, predict," the onsite measurements can be related to a long-term reference, a nearby airport weather station for example, to reduce the uncertainty associated with the variability of the wind resource over time.

Meteorological towers or remote sensing devices measure the wind conditions at only a few locations across a project area. Computer-based wind flow models, using the previously validated and analyzed wind data, can be used to estimate the wind resource across the wider project area. The resulting wind maps are used to generate estimates of the energy production for an entire wind farm, as well as inform the design of the turbine layout to help maximize production. In order to achieve a defensible estimate of energy production, it is necessary to possess a thorough understanding of the uncertainty that is inherent throughout the wind resource assessment process.

Section 1

1. INTRODUCTION

For any power plant to generate electricity, it needs fuel. For a wind power plant, that fuel is the wind.

Wind resource assessment is the collection of technologies and analytical methods that are used to estimate how much fuel will be available for a wind power plant over the course of its useful life. This is the single most important piece of information for determining how much energy the plant will produce, and ultimately how much money it will earn for its owners. The resulting estimates of energy production are most often used by project developers to secure funding from investors to build a project. For a wind project to be successful, accurate wind resource assessment is essential. Given the cost and effort associated with conducting a wind resource assessment campaign, this type of undertaking is most often only associated with utility-scale projects, consisting of multiple wind turbines with nominal generating capacities upwards of 1.0 megawatts each.

The technology for measuring wind speeds has been available for centuries. The cup anemometer - the most commonly used type for wind resource assessment - was developed in the mid-19th century, and its basic design (three or four cups attached to a vertical, rotating axis) has scarcely changed since.

Yet an accurate estimate of the energy production of a large wind project depends on much more than being able to measure the wind speed at a particular time and place. The requirement is to characterize atmospheric conditions at the wind project site over a very wide range of spatial and temporal scales - from meters to kilometers, and from seconds to years. This entails a blend of techniques from the mundane to the sophisticated, honed through years of sometimes onerous experience into a rigorous process.

The details of that process are the subject of this handbook. Before diving into them, however, we should back up a little and set wind resource assessment in context. Where does the wind come from? What are its key characteristics? And how is it converted to electricity in a wind power plant?

1.1. WHERE DO WINDS COME FROM?

The simple answer to this question is that the air moves in response to pressure differences, or gradients, between different parts of the earth's surface. An air mass tends to move towards a zone of low pressure and away from a zone of high pressure. Left alone, the resulting wind would eventually equalize the pressure difference, and it would die away.

The reason air pressure gradients never completely disappear is because they are continually being powered by uneven solar heating of the earth's surface. When the surface heats up, the air above it expands and rises, and the pressure drops. When there is surface cooling, the opposite process occurs, and the pressure rises. Due to differences in the amount of solar radiation received and retained at different points on the earth's surface, variations in surface temperature and pressure, large and small, are continually being created. Thus, there is always wind at least somewhere on the planet.

While uneven solar heating is ultimately the wind's driving force, the earth's rotation plays a key role. The Coriolis effect[1] causes air moving towards the poles to veer to the east, while air heading for the equator veers to the west. Its influence means that the wind never moves directly towards a zone of low pressure, but rather circles around it along lines of constant pressure. This is the origin of the cyclonic winds in hurricanes.

By far the most important temperature gradient driving global wind patterns is that between the equator and the poles. Combined with the Coriolis effect, it is responsible for the well-known equatorial trade winds and mid-latitude westerlies (Figure 1-1). At the equator, relatively warm, moist air has a tendency to rise through convection to a high altitude. This draws air in from middle latitudes towards the equator, and thereby sets up a circulation known as a Hadley cell (after the 19th century meteorologist who first explained the phenomenon). Because of the Coriolis effect, the inflowing air turns towards the west, creating the easterly trade winds.[2]

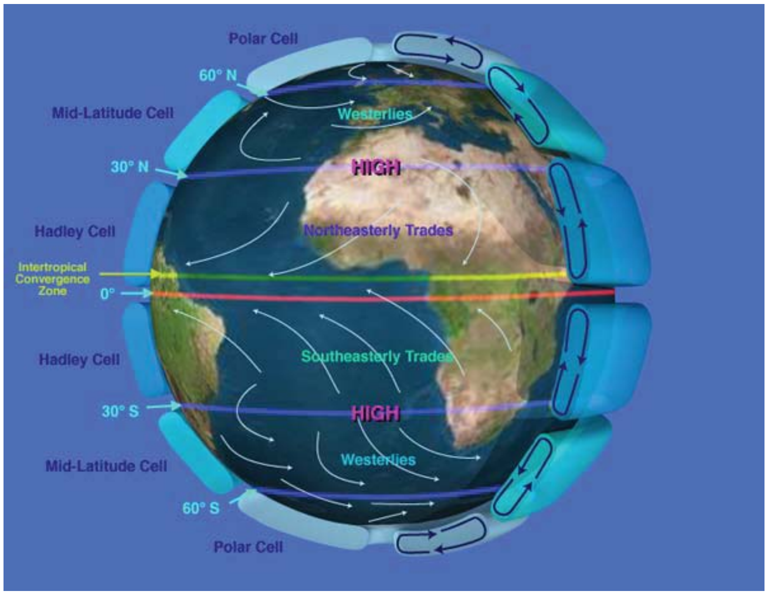


Figure 1-1 The main global atmospheric circulations. (Source: NASA/JPL-Caltech)

[1] The Coriolis effect is a property of observing motions from a rotating reference frame - the earth. The earth's surface moves faster around the axis at the equator than it does closer to the poles. If an object moves freely toward the equator, the surface beneath it speeds up towards the east. From the perspective of an observer on the surface, the object appears to turn towards the west.
[2] By convention, wind direction is denoted by the direction the wind comes *from*. If the air is moving toward the north, it is said to be a southerly wind.

A similar circulation pattern known as a polar cell is set up between high latitudes and the poles. Lying between the polar and Hadley cells are the mid-latitude (Ferrel) cells, which circulate in the opposite direction. Unlike the others they are not driven by convection but rather by the action of sinking and rising air from the adjacent cells. Once again the Coriolis effect asserts itself as the air flowing poleward along the surface turns east, creating the westerlies. The westerlies are the reason wind resources tend to be so good in the temperate and high latitudes (from around 35 ºN to 65 ºN) of North America, Europe, and Asia, as well as the southern extremes of Africa, South America, and Australia.

Superimposed on these global circulation patterns are many regional patterns. Large land masses heat up and cool down more rapidly than the oceans, and even within land masses there are variations in surface heating - for instance, between a snow-covered mountain top and a green valley below, or between a desert and a cultivated plain. The resulting temperature gradients set up what are called mesoscale atmospheric circulations - mesoscale because they are in between the global scale and the local scale, or microscale. The most familiar of such circulations is the sea breeze: During a typical summer day, the land becomes warmer than the ocean, the pressure drops as the air above it expands and rises, and relatively cool, dense air is pulled in from the ocean. At night, the process reverses, resulting in a land breeze. Normally sea breezes are weak, but where the wind is concentrated by terrain, they can have a powerful effect. This is the primary mechanism behind the very strong winds found in coastal mountain passes in California, Oregon, and Washington.

As these examples suggest, while temperature and pressure differences create winds, they can be strongly influenced by topography and land surface conditions as well. Where the wind is driven over a rise in the terrain - and especially over a ridge that lies transverse to the flow - there can be a significant acceleration, as the air mass must move more quickly to compensate for the more restricted vertical space. This effect is similar to how water accelerates through the constricted nozzle of a hose. Thanks to this effect, many of the best wind sites in the United States are on elevated terrain features of some kind, ranging from sharp mountain ranges in West Virginia to gentle rolling hills in Iowa. Where the air near the surface tends to be cooler and heavier than the air it is displacing - as in the sea breeze example above - it has a greater tendency to find paths around the high ground rather than over it. In such situations, it is often the mountain passes rather than the mountain tops that have the best wind.

Surface vegetation and other elements of land cover, such as houses and other structures, also play an important role. This is often characterized in meteorology by a parameter called the surface roughness length. Because of the friction, or drag, exerts on the lower atmosphere, wind speeds near the ground tend to be lower in areas of higher roughness. This is one of the main reasons the eastern United States has fewer good wind sites than the Great Plains. Conversely, the relatively low roughness of open water helps explain why wind resources generally improve with distance offshore.

1.2. KEY CHARACTERISTICS OF THE WIND

The annual average wind speed is often mentioned as a way to rate or rank wind project sites. These days, most wind project development is occurring at sites with a mean wind speed at the hub height of the turbine of over 6.5 m/s. This measure of the wind resource is relatively crude, however. To provide the basis for an accurate estimate of energy production, the wind resource must be characterized not only by the mean speed but by variations in speed and direction, as well as air density, in both time and space.

The Temporal Dimension

The very short time scales of seconds and less is the domain of turbulence, the general term for very rapid fluctuations in wind speed and direction caused by passing pressure disturbances, or eddies. We typically experience turbulence as wind gusts. Turbulence is a critical mechanism for the atmosphere to gradually shed the energy built up by solar radiation. Unfortunately, it can have no positive role in power production because wind turbines cannot respond fast enough to convert the speed variations to power output. In fact, high turbulence generally causes a decrease in power output as the turbine often finds itself with the wrong pitch setting or not pointing directly into the wind. In addition, turbulence contributes to wear in mechanical components such as pitch actuators and yaw motors. For this reason, manufacturers may not warrant their turbines at sites where the turbulence exceeds the design range. Knowledge of turbulence at a site is thus very important for wind plant assessment.

Fluctuations in wind speed and direction also occur over periods of minutes to hours. Unlike true turbulence, however, such fluctuations are readily captured by wind turbines, resulting at times in rapid changes in output. This is a time frame of great interest for electric power system operators, who must respond to the wind fluctuations with corresponding changes in the output of other plants on their systems to maintain steady output. It is consequently a focus of short-term wind energy forecasting.

On a time scale of 12 to 24 hours are variations associated with the daily pattern of solar heating and radiative cooling of the earth's surface. Depending on the height above ground and the nature of the wind climate, wind speeds at a given location typically peak either mid-afternoon or at night. Which pattern predominates can have a significant impact on plant revenues in markets that price power according to demand or time of day. The ideal in most parts of the country is an afternoon-peaking wind resource, but this is found usually only where the dominant wind pattern is a mesoscale circulation. At the vast majority of wind sites in North America, at the heights of modern, large wind turbines, the wind resource peaks at night.

The influence of the seasons begins at time scales of months. In most of North America - again with the exception of sites with strong warm-weather mesoscale circulations - the best winds usually occur in the winter months, while the summer is much less windy. Because of this strong variation, it is difficult to get an accurate fix on the mean wind resource with a measurement campaign spanning much less than a full year. Furthermore, as with diurnal variations, seasonal variations can have a major impact on plant revenues. Power prices are usually highest in summer on a summer-peaking system and in winter on a winter-peaking system.

At annual and longer time scales, we enter the domain of regional, hemispheric, and global climate oscillations, such as the famous El Niño. These oscillations - as well as chaotic processes - account for much of the variability in wind climate from year to year. They are the main reason it is necessary to correct wind measurements taken at a site to the long-term historical norm. It is critical to take annual variability into account in wind plant financial models, since revenues will tend to rise and fall with the wind resource.

The Spatial Dimension

The spatial dimension of wind resource assessment is especially important for wind plant design. Most wind power plants have more than one wind turbine. To predict the total power production, it is necessary to understand how the wind resource varies among the turbines. This is especially challenging in complex, mountainous terrain, where topographic influences are strong. One approach is to measure the wind at numerous locations within the wind project area. Even then, it is usually necessary to extrapolate the observed wind resource to other locations using some kind of model, typically a numerical wind flow model.

The spatial scales of interest are related to the size of wind turbines and the dimensions of wind power projects. The rotor diameter of modern, large wind turbines is typically 70 m to 100 m. Wind turbines are spaced some 200 m to 800 m apart, and large wind projects can span a region as wide as 10 km to 30 km. Within this overall range, a detailed map of the variations is essential for the optimal placement of wind turbines and accurate estimates of energy production.

The vertical dimension is just as important. The variation in speed with height is known as wind shear. In most places, the shear is positive, meaning the speed increases with increasing height. Knowing the shear is important for projecting wind speed measurements from one height (such as the top of a mast) to another (such as the hub height of a turbine). Extreme wind shear (either positive or negative) can cause extra wear and tear on turbine components as well as losses in energy production. The shear is typically measured using simultaneous speed measurements at more than one height on a mast, or with a remote sensing device such as a sodar or lidar.

Other Characteristics of the Wind Resource

Although wind speed is the dominant characteristic of the wind resource, there are other important ones, including direction, air density, icing frequency, and other conditions, all of which need to be well characterized to produce the most accurate possible energy production estimate.

Knowledge of the frequency distribution of wind directions is key for optimizing the layout of wind turbines to minimize wake interference between them. Turbines are generally spaced farther apart along the predominant wind direction than along other directions.

Air density determines the amount of energy available in the wind at a particular wind speed: the greater the density, the more energy is available, and the more electric power a turbine can produce. Air density depends mainly on temperature and elevation.

A substantial amount of ice accumulating on turbine blades can significantly reduce power production as it disrupts the carefully designed blade airfoil, and can become so severe that turbines must be shut down. The two main mechanisms of ice accumulation are freezing precipitation and direct deposition (rime ice). Other conditions potentially affecting turbine performance include dust and soil, insects.

1.3. WIND POWER PLANTS

This handbook is not the place for an in-depth treatment of wind plant design and turbine technology. Nevertheless, it is important for wind resource analysts to be familiar with their basic elements.

Conceptually, a wind turbine is a simple machine. The motion of the air is converted by the blades - lifting airfoils very similar to airplane wings - to torque on a shaft. The torque turns a power generator, and the power flows to the grid.

The simple picture of utility-scale wind turbines in Figure 1-2 disguises many complex design features. The typical modern large wind turbine, 65 m to 100 m tall at the hub with a rotor 70 m to 100 m in diameter and with a rated capacity of 1 megawatt (MW) to 5 MW, is an immense, complicated

Figure 1-2 Utility-scale wind turbines. (Source: AWS Truepower)

machine that must operate reliably and at peak efficiency under a wide range of wind conditions. This requires numerous components - from nacelle anemometers to pitch actuators and yaw drives to power electronics - working together in an integrated system.

Perhaps the key characteristic of a wind turbine from the perspective of wind resource assessment is the turbine power curve (Figure 1-3). This describes the power output as a function of wind speed measured at the hub. It is characterized by a cut-in speed, typically around 3 or 4 m/s; a steeply sloping portion, where the turbine output increases rapidly with speed; a rated speed, typically around 13-15 m/s, where the turbine reaches its rated capacity; and a cut-out speed, above which the turbine control software shuts the turbine down for its protection. At any given speed, most turbines (those that are pitch regulated) strive to maintain the maximum possible output by frequently adjusting the blade pitch and rotor yaw.

Although well-operated turbines are finely tuned machines, it is wrong to assume that a turbine produces exactly the expected power at every speed. Blade wear and soiling, equipment wear, and control software settings can all cause turbines to deviate from their ideal power curve. In addition, power output depends on wind conditions, such as turbulence and the inclination of the wind flow relative to horizontal. Taking account of such variations is part of estimating energy production - and it starts with a detailed understanding of the wind resource.

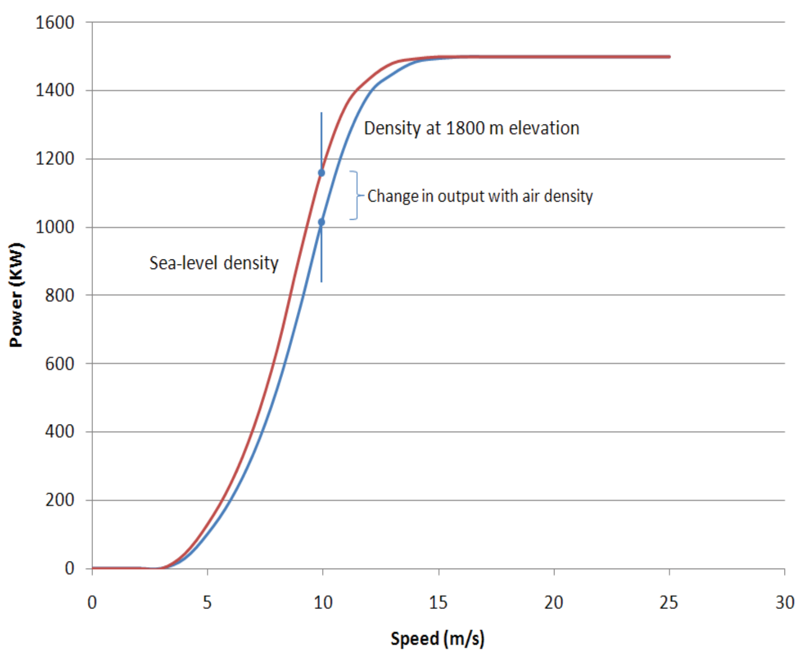


Figure 1-3 Typical power curve for a 1.5-MW turbine at two different air densities. (Source: AWS Truepower)

Wind projects are likewise conceptually simple: they are just arrays of wind turbines linked through a power collection system to the power grid (Figure 1-4). Designing a wind project, however, often entails delicate tradeoffs between, e.g., total plant output, construction cost, and energy losses. The process begins with a detailed picture of how the wind resource is distributed across the site, supported by measurements and spatial modeling of some kind. Another important consideration is wake interference between turbines. When a turbine extracts energy from the wind, a zone of reduced wind speed and increased turbulence is created behind it (Figure 1-5). Any turbines that happen to be within this wake may be affected.

Almost every stage of wind project development depends critically on a detailed and accurate picture of the wind resource. That is where this handbook comes in.

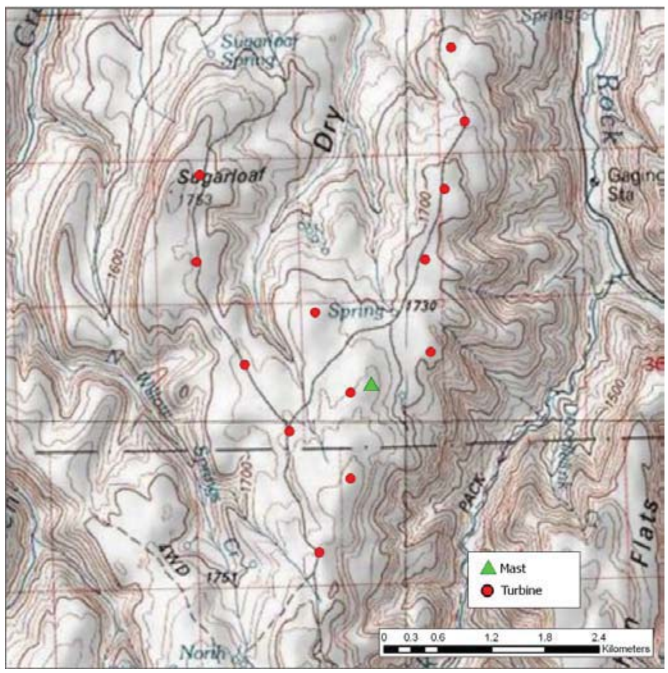


Figure 1-4 Layout of a proposed wind farm. (Source: AWS Truepower)

Figure 1-5 Rare visual evidence of turbine wakes in an offshore wind farm. The increased turbulence behind each turbine causes the water vapor in the air to condense as droplets, forming a visible contrail. The wind speed in each wake is also reduced. (Source: Horns Rev 1 owned by Vattenfall. Photographer Christian Steiness)

1.4. PURPOSE AND ORGANIZATION OF THIS HANDBOOK

This handbook is primarily intended to give guidance to professional practitioners on the accepted methods of wind resource assessment for utility-scale wind farms. The goal is not to impose conformity in every respect. On the contrary, the handbook often highlights areas where there is room for reasonable variation, even disagreement, on the approaches that can be used. A diversity of methods - for example, in wind flow models and sensor types - can be a strength in wind resource assessment if it reduces errors associated with any single approach.

Yet the range of variation nonetheless has limits. It may be acceptable in some cases to install a tower with just two levels of anemometers; never just one. It may be fine to use a new or unusual atmospheric model; never (for sizable wind projects) without anchoring the results with accurate measurements and testing the model's accuracy. What we hope the reader takes away from this handbook is a clear understanding of those limits.

Whenever possible, the handbook goes beyond a cookbook to describe some of the concepts and principles behind the tried-and-true techniques. This, we hope, will empower the reader to make his or her own judgments where conditions depart - as they often do - from the ideal. It should also make for more interesting reading. What the handbook does *not* strive to be is a comprehensive reference on every aspect of wind resource assessment. For those many interesting topics, there are the standards published by the International Electrotechnical Commission (IEC), the proceedings of the many wind conferences that occur every year in the United States and around the world, as well as a number of Internet-based resources.

The handbook is organized in order of the main stages of wind resource assessment. The first several chapters focus on the nuts and bolts of conducting a measurement campaign. It starts with the guiding principles for a wind measurement program. Then it moves through site selection; measurement parameters and tower instrumentation; tower installation and maintenance; and data collection and handling. The last chapter in this group, Chapter 8, focuses on remote sensing (lidar and sodar). The next section of the handbook addresses the analysis. It starts with data validation, and then covers how to characterize and present the wind resource. Additional key topics include extrapolating the wind resource estimates to hub height, correcting short-term measurements to long-term historical conditions, and wind flow modeling. The last chapter, Chapter 14, discusses uncertainty. Last, additional reference material is provided in various appendices.

PART I

WIND MONITORING

Section 2

2. GUIDING PRINCIPLES OF A WIND RESOURCE ASSESSMENT CAMPAIGN

A wind resource assessment campaign is similar in many respects to other technical projects. It requires planning and coordination and is constrained by budget and schedule limitations. It demands a clear set of objectives so the best approach is selected and the desired results are obtained. Its ultimate success rests on the quality of the program's assembled assets — sound siting and measurement techniques, trained staff, quality equipment, and thorough data analysis techniques.

This chapter provides an introduction to the design and implementation of a wind resource assessment campaign and identifies where these concepts are expounded upon within the handbook.

A graphical summary of the project lifecycle for a utility wind energy project is provided in Figure 2-1. The wind resource assessment campaign represents the first step in the project development process. To learn more about wind energy projects beyond the wind resource assessment phase, NYSERDA's Wind Energy Toolkit provides an overview of the development process from the initial siting process through project decommissioning.[3]

Several approaches are available when investigating the wind resource within a given land area. The preferred approach will depend on your wind energy program objectives and on previous experience with wind resource assessment in the region and in similar terrain. These approaches can be categorized as three main stages of wind resource assessment: site identification, preliminary resource assessment, and micrositing.

Chapter 2 At-a-Glance

- A wind resource assessment campaign is comprised of three main components: site identification, preliminary resource assessment, and micrositing.
- Geographic Information Systems (GIS) can be very useful in organizing and interpreting geographical data at all stages of the campaign.
- Preliminary resource assessment involves a clearly defined measurement plan, including tower placement, height, instrumentation, and other elements.
- Instituting a quality assurance plan is essential to maximize the utility of the measurement campaign.
- Key elements of micrositing include additional measurements, data validation, adjustment for wind shear and long-term wind climate, numerical wind flow modeling, and uncertainty estimation.

[3] NYSERDA's Wind Energy Toolkit: www.powernaturally.org/programs/wind/toolkit

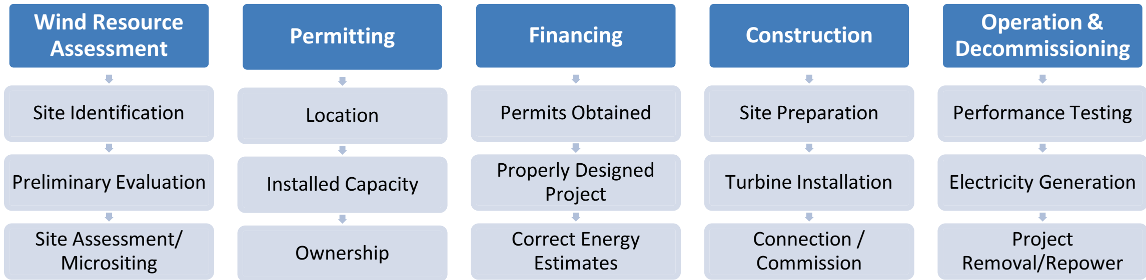


Figure 2-1 Graphical summary of a utility scale wind energy project lifecycle. (Source: AWS Truepower)

2.1. SITE IDENTIFICATION

The first stage of the wind resource assessment process identifies potential wind development sites for further investigation. This process screens a relatively large region (e.g., a county or state) for attractive sites based on information such as wind maps and publically available wind data. It also accounts for favorable and unfavorable aspects, such as constructability, access, and environmental sensitivities. Details on site screening techniques are provided in Chapter 3.

As a first step in determining an area's development potential, it is recommended that geographic data be collected and compiled in a Geographic Information System (GIS). This helps the user work efficiently and make accurate decisions during the site-selection process. The most useful geographic information to obtain and map during this phase include the following:

- Wind resource maps
- Terrain data
- Project boundary
- Water bodies
- Roads and paths
- Land cover data
- Transmission line and substation locations
- Buildings
- Pipelines (natural gas, oil)
- Competing projects
- Exclusions
- Permitting requirements
- Radar and airspace restrictions

(See Appendix C for useful sources of GIS data within the US and Canada).

Once a GIS project has been created, appropriate criteria can be applied to select candidate sites.

After some number of candidate sites have been selected, much of the monitoring design can be determined in a virtual environment. A GIS is particularly useful for determining the most effective locations to install monitoring towers. Ideally, the GIS will change through time as the project plan evolves to keep relevant information up to date and aid in the decision-making process.

2.2. PRELIMINARY RESOURCE ASSESSMENT

Once a candidate site(s) is identified, the second stage involves a preliminary characterization of the wind resource. This is when the first wind monitoring towers are likely to be installed. The most common objectives of the wind monitoring program at this stage are to:

- Determine or verify whether sufficient wind resources exist within the site to justify further site-specific investigations
- Compare the wind resource between different sites to distinguish relative development potential
- Obtain representative data for estimating the performance and economic viability of selected wind turbine models

Chapters 4 to 8 in this handbook are devoted to providing information and recommendations in support of this phase of the wind resource assessment process, including guidelines for designing and carrying out a measurement program.

Wind Monitoring Campaign Design

The general objective of a wind monitoring campaign is to obtain the best possible understanding of the wind resource at the turbine hub height and through the rotor plane across the project area. This objective can be achieved through a variety of monitoring options, including tower distribution, height, and instrumentation and ground-based remote sensing. Once the measurement phase is substantially completed, it is followed by data analysis and modeling. Chapters 3 through 5 provide guidance in designing a wind monitoring campaign, Chapter 8 discusses remote sensing devices.

Tower Distribution. The location and distribution of meteorological towers within a project area are designed to minimize the uncertainty of the wind resource at potential turbine locations. Important considerations that are taken into account during the tower siting process include, but are not limited to, the following:

- Similarity or representativeness of the terrain to the larger project area
- Ability to capture the diversity of conditions experienced by future turbines
- Distance to future turbines, if the turbine layout is known
- Multiple masts, if needed

Additional information regarding the proper placement of meteorological masts is provided in Chapter 3.

Tower Height. Sixty-meter meteorological towers are the mainstay of most wind monitoring programs. Even taller towers as well as remote sensing systems may be employed, with the main objective of measuring the wind resource at the hub height (and above) of the proposed wind turbines. The direct measurement at hub height, rather than extrapolation from lower measurement heights, reduces uncertainties in the wind resource. For large wind projects (>100 MW), it is recommended that at least one in three meteorological towers be of hub height. In general, the need for hub-height towers is driven by the perceived uncertainty in the site's wind shear; if the shear is well understood, hub-height towers may have limited value. At sites where shear is difficult to characterize, on the other hand, hub-height towers may be highly cost effective, although budgetary and siting constraints may still lead to a mix of tower heights being deployed. Additional information on hub-height towers can be found in Chapter 3.

Tower Instrumentation. The core of the monitoring program is the collection of wind speed, wind direction, and air temperature data. Wind speed data are the most important indicator of a site's wind energy resource. Multiple measurement heights are essential to determine a site's wind shear characteristics. Wind direction frequency information is important for optimizing the layout of wind turbines within a wind farm. Air temperature measurements help to provide additional information about the site conditions and to determine air density.

Specific recommendations for standard instrumentation packages are discussed in detail in chapters 4 and 5. These sections also outline exceptions to the typical instrument package that can be implemented based upon the characteristics of the site or project. These exceptions demonstrate the need for a detailed campaign design that takes all project variables into account.

Ground-Based Remote Sensing. Sodar (sonic detection and ranging) and lidar (light detection and ranging), two relatively recent options for measuring wind speed, can be useful for spot-checking the wind resource at different points within the project area and for measuring the wind shear throughout the rotor plane. Short-term (4-6 week) campaigns are typical, but longer or multiple campaigns may be advisable for large projects (greater than 100 MW), in complex terrain, or for projects where significant seasonal variation of shear is expected. More information on remote sensing technology can be found in Chapter 8.

Measurement Plan. Common to all monitoring programs is the need for a measurement plan. Its purpose is to ensure that all facets of the wind monitoring program combine to provide the data needed to meet the wind energy program objectives. It should be documented in writing, and reviewed and approved by the project participants before it is implemented. The plan should specify the following elements:

- Measurement parameters (e.g., speed, direction, temperature)
- Equipment type, quality, and cost
- Equipment monitoring heights, orientations
- Number and location of monitoring masts
- Minimum desired measurement accuracy, duration, and data recovery

- Data sampling and recording intervals
- Parties responsible for equipment installation, maintenance, data validation, and reporting
- Data transmission, screening, and processing procedures
- Quality control measures
- Data reporting intervals and format.

The recommended minimum duration of the wind monitoring is one year (12 consecutive months), but a longer period produces more reliable results. The data recovery for all measured parameters should be as high as possible, with a target for most tower sensors of at least 90%, with few or no extended data gaps. The rate actually achieved will depend on a number of factors, including the remoteness of the site, weather conditions, the type and redundancy of instruments, and methods of data collection.

Monitoring Strategy

At the core of the monitoring strategy is good management, qualified staff, and adequate resources. It is best if everyone involved understands the roles and responsibilities of each participant and the lines of authority and accountability. Everyone should be familiar with the program's overall objectives, measurement plan, and schedule. Communications among the players should be frequent and open.

Because of the complexities of wind monitoring, it is recommended that the project team include at least one person with field measurement experience. Data analysis, interpretation, and computer skills are also important assets. Available staff and material resources must be commensurate with the measurement program's objectives. High standards of data accuracy and completeness require appropriate levels of staffing, an investment in quality equipment and tools, prompt responsiveness to unscheduled events (e.g., equipment outages), access to spare parts, routine site visits, and timely review of the data.

Two components that are integral to the monitoring strategy are station maintenance and the data collection process.

Station Operation and Maintenance. Ongoing maintenance and careful documentation of the wind resource monitoring station is necessary to preserve the integrity of the measurement campaign and to achieve the goals of the measurement plan. It is recommended that a simple but thorough operation and maintenance plan be instituted. This plan should incorporate various quality assurance measures and provide procedural guidelines for all program personnel. Specific recommendations for the operation and maintenance of wind resource monitoring stations are provided in Chapter 6.

Data Collection and Handling. The objective of the data collection and handling process is to ensure that the data are available for analysis and protected from corruption or loss. Chapter 7 provides background information about how data are stored locally at the monitoring station, as well as how they can be retrieved and protected. Suggested content for data transmission documentation is also provided; these records can provide important quality-control information regarding equipment performance and data quality.

Quality Assurance Plan

An essential part of every measurement program is the quality assurance plan, an organized and detailed action agenda for guaranteeing the successful collection of high-quality data. The plan should be prepared in writing once the measurement plan is completed.

- **Quality Assurance Policy:** The program manager should establish and endorse the quality assurance plan, thus giving it credibility for all personnel.

- **Quality Assurance Coordinator:** The link between the plan and the program management is the quality assurance coordinator. Ideally, this person will be knowledgeable of the routine requirements for collecting valid data. If the quality assurance plan is to be taken seriously, this person must be authorized to ensure that all personnel are properly trained, correct procedures are followed, and corrective measures are taken. In addition, the coordinator should maintain the proper documentation in an organized format.

Data quality is usually measured by representativeness, accuracy, and completeness. The quality assurance plan relies heavily on the documentation of the procedures involved to support claims of data quality. It is recommended that the quality assurance plan include the following components:

- Equipment procurement tied to the program's specifications
- Equipment calibration method, frequency, and reporting
- Monitoring station installation, verification, and operation and maintenance checklists
- Data collection, screening, and archiving
- Data analysis guidelines (including calculations)
- Data validation methods, flagging criteria, reporting frequency, and format
- Internal audits to document the performance of those responsible for site installation and operation and maintenance, and for data collection and handling.

Another goal of quality assurance is to minimize the uncertainties that unavoidably enter every step of the measurement processes. No tower perfectly represents the entire area it represents, no sensor measures with perfect accuracy, and no data gathered over an extended measurement period perfectly reflect wind conditions a wind plant may experience during its lifetime. Still, if the magnitude of these uncertainties is understood and controlled through a concerted quality assurance plan, the conclusions can be properly qualified to provide useful information.

2.3. MICROSITING

The third stage of wind resource assessment entails a detailed evaluation of the wind resource at the chosen site(s). At this stage, the wind resource is characterized as accurately as possible at all relevant temporal and spatial scales, with the objective of enabling an accurate estimation of energy production and the optimal placement of turbines within the project area. Part 2 of this handbook, chapters 9 to 14, deals with topics of particular importance for this stage, including data validation, long-term climate adjustments, wind flow modeling, and uncertainty.

Data Validation

Once the data from the monitoring system have been successfully transferred to an office computing environment, the data can be validated. During this process, the completeness and reasonableness of the data are assessed and invalid or suspect values are flagged within the data record. This process is also used as an early detection system to identify potential issues with the instrumentation or data logger. Recommended data validation processes are provided in Chapter 9, as well as a discussion of data substitution and averaging and post-validation adjustments.

Characterizing the Observed Wind Resource

After the wind resource data have been validated, they can be analyzed to generate a variety of wind resource statistics that help characterize the site's wind resource. An account of the most common metrics used to describe a wind resource (e.g. wind speed, shear, turbulence intensity, and wind power density) is provided in Chapter 10, along with the associated equations and examples of typical values.

Estimating the Hub-Height Resource

Estimating a wind turbine's energy production often requires extrapolating the measured data from the top height of a tower to the intended turbine hub height. The task requires a careful and often subjective analysis of information about the site, including the local meteorology, topography, and land cover, as well as the measured wind shear. The information in Chapter 11 will help guide the analyst through this complex process, and increase his or her understanding of the factors involved.

The Climate-Adjustment Process

One of the last major steps in the analysis process involves adjusting the observed wind measurements to the site's historical norm. The objective of this process is to understand how the measurements compare to the conditions that normally occur. This is important because wind speeds can vary substantially from the norm, making the measurement from a short-term wind resource assessment campaign potentially misleading. A process known as “measure, correlate, predict” (MCP) is used to relate onsite measurements to a long-term reference, thereby reducing the uncertainty of associated energy estimates. Chapter 12 provides an overview of the MCP process.

Wind Flow Modeling

Since onsite measurements are limited to just a few locations within the project area, wind flow modeling, most often done with computer software, must generally be used to estimate the wind resource at all locations where wind turbines might be deployed. Chapter 13 provides an overview of the types of wind flow models that are available, the application of such models, and the uncertainty associated with using them.

Uncertainty in Wind Resource Assessment

A sound understanding of the inherent uncertainty associated with the wind resource assessment process is necessary to achieve a defensible estimate of energy production that can be used as the basis for project financing. Chapter 14 reviews the potential sources of uncertainty within the wind resource assessment process, how they can be estimated, and provides typical uncertainty values for the various sources.

Section 3

3. SITING OF MONITORING SITES

The main objectives of a siting program is to select candidate wind project sites as well as locations for wind monitoring systems. There are three main steps in the siting effort:

- Identification of potential wind development sites
- Ranking and inspection of candidate sites
- Selection of tower and other monitoring location(s) within the candidate sites

Since the region to be surveyed can sometimes be quite large - as large as a United States county or state - the site selection process should be designed so it efficiently focuses on the most suitable areas. Sections 3.1 and 3.2 discuss several industry-accepted siting tools and techniques. Sections 3.3 through 3.6 outline steps to be taken following initial site identification. These include field surveys, choosing appropriate tower locations, and obtaining necessary permits prior to tower installation.

> ***Chapter 3 At-a-Glance***
>
> - Geographical Information Systems allow the developer to organize and analyze important information regarding the region to be surveyed and candidate project sites.
> - Candidate sites should be visited to ground-truth the information used in the site-screening process.
> - The main objective of siting monitoring systems is to obtain wind resource data at locations that are representative of where turbines might be placed. The temptation to select only the windiest or most well-exposed spots should be avoided.
> - A number of federal, state, and local agencies may have to be consulted prior to the installation of a wind monitoring tower.
> - Developers will typically secure an option agreement with landowners during the monitoring campaign. If a wind project is constructed, the developer will likely lease the land.

3.1. USE OF GIS FOR SITE SELECTION

Geographic Information Systems (GIS) have become an integral part of the site selection process. The site-screening techniques outlined in sections 3.2 and 3.3 can be greatly facilitated in a digital environment using GIS. The use of GIS overlay analysis allows for additional site variables, along with terrain and wind speed, to be considered. They may include:

- Proximity to transmission lines
- Site accessibility
- Land cover
- Land-use restrictions
- Environmental concerns and community sensitivities
- Significant obstacles

Generally, wind project developers try to minimize the distance from their project site to existing transmission lines. The substantial cost and risk associated with building long transmission lines can affect a project's feasibility. GIS enables the distance and construction cost to be estimated. Site accessibility can be considered through the analysis of topographical and land cover data. Particularly steep terrain and dense land cover can increase infrastructure and construction costs or preclude development altogether. Land-use restrictions help to define the project's buildable area; exclusion zones may be specified according to environmental laws and regulations as well as community sensitivities. Once potential sites are identified, GIS can be utilized in conjunction with high-resolution aerial imagery to facilitate an initial desktop site inspection and site ranking.

The placement of the monitoring systems follows the site selection process. With the information that was gathered in the first phase, the project area can be analyzed for suitable monitoring locations. The objective is to select locations that are representative of the conditions that the turbines will eventually experience. The placement of the monitoring system is discussed further in section 3.4 below.

3.2. USE OF WIND RESOURCE INFORMATION

Wind resource information is extremely important in the early stage of the siting process. Though insufficient by itself to determine project feasibility, such information can suggest the range of performance to be expected by wind projects that might be built in the region and point toward potential sites. Two common sources of data used to gain an initial estimate of the wind resource are regional wind maps and publicly available wind measurements

Wind Resource Maps

Regional wind resource maps are a useful starting point for identifying potentially attractive wind resource areas. They have the added benefit of being compatible with GIS. Reasonably accurate and detailed wind resource maps have been produced using mesoscale weather models, microscale wind flow models, and high-resolution elevation and land cover data. Quoted uncertainties in the mean speed typically fall in the range of several tenths to a meter per second, and the spatial resolution of regional maps ranges from 200 m to 5 km. Confidence in the maps is highest in relatively simple terrain and where ample validation data, provided by high-quality measurements, exist. A greater uncertainty can be expected in complex terrain and data-sparse areas. Although regional wind maps are useful, they are usually not accurate enough to replace onsite measurements. (Exceptions may be made for small wind projects where the added certainty of onsite measurements does not justify the cost of a wind monitoring campaign.) Sources of wind resource maps for the United States are listed in Appendix C.

Some care is required to interpret wind resource maps. Most maps present estimates of the long-term mean wind speed at a particular height above ground. Some indicate the expected mean wind power density in watts per square meter of swept rotor area. Neither parameter can be translated directly into production by a wind turbine, which depends on other factors such as the speed frequency distribution, air density, and turbulence, as well as on the specific turbine model and hub height. Some wind map vendors provide such supplemental information upon request, including estimates of capacity factor for particular turbine models.

As a general rule, however, mean wind speeds greater than 6.5 m/s at a height of 80 m above ground are required to be of interest for utility-scale wind projects. In some regions, lower mean speeds may be adequate depending on local power purchase prices and available renewable-energy incentives and mandates. As wind power development spreads, it is likely that less-windy sites will become increasingly attractive.

Wind Measurements

Publicly available wind data can be useful for assessing the wind resource in a region, especially if the wind monitoring stations are in locations that are representative of sites of interest for wind projects. An example would be a tall tower on a ridge line that runs parallel to a similar ridge under consideration. Tall towers instrumented specifically for wind energy are preferred, but airport and other weather stations may provide a helpful indication of the wind resource as well. In all cases it is important to obtain as much information as possible regarding each station to determine whether or not the data are reliable. Several elements should be considered in this determination:

- Station location
- Tower type and dimensions
- Local topography, obstacles, and surface roughness
- Sensor heights, boom orientations, and distances from tower
- Sensor maintenance protocol and records
- Duration of data record
- Quality-control (QC) and analysis applied to the data

Wind data tend to be more representative of the surrounding area where the terrain is relatively flat. In complex terrain or near coastlines, the ability to reliably extrapolate the information beyond a station's immediate vicinity is more limited and may require expert judgment and wind flow modeling. Even in flat terrain, good exposure to the wind is essential, especially for short towers. Measurements taken in obstructed areas or on rooftops should not be used unless there is good reason to believe that the effects of the obstructions are small. In any event, data from existing meteorological towers, except in rare instances, are unlikely to be able to replace onsite measurements from a wind monitoring campaign.

Typical tall-tower anemometer heights are 30 m to 60 m, while heights for other stations may be anywhere from 3 m to 20 m. When comparing data from different stations, all wind speeds should be extrapolated to a common reference height (e.g., 80 m, a typical wind turbine hub height). Wind speeds can be adjusted to another height using the following form of the power law equation:

$$v_2 = v_1 \left(\frac{h_2}{h_1}\right)^{\alpha}$$ **Equation 3-1**

where:

v_2 = the unknown speed at height h_2
v_1 = the known wind speed at the measurement height h_1
α = the wind shear exponent.

The uncertainty in the projected speed depends on both the ratio of heights and the uncertainty in the wind shear exponent. If the upper height is a large multiple of the lower height, the uncertainty may be quite large. For example, extrapolating from 10 m to 80 m may entail an uncertainty of 10%-30% in the resulting speed.

For most publicly available data sets, the wind shear exponent will not be known (and even if published, may not be reliable). Wind shear exponents vary widely depending on vegetation cover, terrain, and the general climate. (In addition, the shear can vary greatly by time of day, though this fact is usually less important for regional wind resource assessments.) The following table presents typical ranges of annual mean shear exponent in different parts of the country and in different site conditions.

Region	Site Conditions	Approximate Range of Annual Mean Wind Shear Exponent
Central US/Great Plains	Open, relatively flat	0.16 - 0.19
Eastern US	Cleared, sharp ridgeline	0.18 - 0.25
	Wooded, broad ridgeline	0.22 - 0.30
	Wooded valley or plain	0.25 - 0.40
Pacific Northwest	Open ridgelines	0.05 - 0.15
Southern California	Grassland and desert	0.00 - 0.15
New Mexico/ Arizona	Open, rolling	0.12 - 0.20
Hawaii, Southern Coastal	Open coastal or island	0.08 - 0.20
Tropical Offshore	Warm water	0.07 - 0.10
Temperate Offshore	Cold water	0.12 - 0.15

Table 3-1 Approximate wind shear exponent ranges in the US.

Ideally, data sets should be at least one year in duration to reduce the effect of seasonal and interannual variations, and provide consistent data for at least 90 percent of that period. A useful format is a time series of hourly or 10-minute wind speed and wind direction measurements, which can be analyzed for a number of wind characteristics such as diurnal and seasonal patterns and interannual variations. In some instances, wind data summaries may be available. Although convenient, such summaries should be used with caution unless the analyst is familiar with the quality-control (QC) procedures and analytical methods used and is confident they were correctly applied. Otherwise, it is usually best to perform one's own analysis from the original data.

3.3. FIELD SURVEYS

It is recommended that visits be conducted to all of the selected candidate wind project sites. The main goals are to assess site conditions and select final locations for monitoring systems. The following items can be documented during the site visit:

- Locations of significant obstructions
- Accessibility to the site
- Potential impact on local aesthetics
- Cellular phone service reliability
- Possible wind monitoring locations (site coordinates, accessibility, and surroundings)

The evaluator can use a detailed topographic map of the area to plan the visit and note pertinent features. A Global Positioning System (GPS) can also be used during the visit to record the exact location (latitude, longitude, and elevation) of each point of interest. The GPS can be linked to a laptop running GIS software. A video or still camera record is also useful. When assessing a proposed tower location, the evaluator can also determine the soil conditions so the proper anchor type can be chosen if a guyed meteorological tower is to be installed. (For more information about soil conditions and anchor types see Section 5.6: Tower Installation.) In forested settings, it should be determined whether tree clearing will be necessary for tower installation.

Field visits also provide an opportunity to become acquainted with landowners who may be involved in or affected by the proposed wind project. The monitoring program's objectives can be presented in a friendly, face-to-face conversation, and the landowner's questions and concerns should be noted and addressed, if possible.

While wind turbines are accepted in many parts of the country, environmental and esthetic issues can still present real obstacles to any project. There is no universal or consistent view of what is or is not pleasing to the eye, so the evaluator must rely on his or her judgment based on the character of the landscape, conversations with local residents, and the proximity of public viewing areas. It is in the project's best interests to investigate this topic in-depth during the initial site evaluation. Detailed visual simulations can be created to model how a proposed project will look from a variety of locations and in different light conditions. This type of analysis can help the community understand a project's possible impact and help developers to identify where a mitigation plan might be required. A detailed examination of this issue is beyond the scope of this handbook. For more information, refer to the bibliography.

3.4. TOWER PLACEMENT

There are two distinct types of monitoring towers: dedicated towers constructed specifically for wind resource monitoring, and pre-existing towers, which are most often instrumented for communications.

Dedicated Towers

Several important guidelines should be followed when choosing the locations for new, dedicated monitoring towers:

- Place the towers as far away as possible from significant obstructions that would not be representative of obstructions at likely turbine locations;
- For small projects, select a location that is representative of where wind turbines are likely to be sited – not necessarily where the best wind is to be found;
- For large projects, select a diverse set of locations representing the full range of conditions where wind turbines are likely to be sited.

One approach to tower placement is to keep the distance between any proposed turbine and the nearest tower within specified limits. With this method, it is necessary to envision a specific turbine layout before siting the towers. This may help determine the appropriate number of towers and reduce the wind flow modeling uncertainty. While there is no clear industry standard, the following guidelines may be followed.

Project Site	Terrain	Maximum recommended distance between any proposed turbine location and nearest mast*
Simple	Generally flat with uniform surface roughness	5-8 km
Moderately Complex	Inland site with gently rolling hills, coastal site with uniform distance from shore, single ridgeline perpendicular to prevailing wind	3-5 km
Very Complex	Steep geometrically complex ridgelines, coastal site with varying distance from shore, or heavily forested	1-3 km

*Assumes meteorological mast is located within proposed turbine array area.

Table 3-2 Recommended monitoring mast distribution based upon site terrain complexity.

Distance is not the only criterion that should be observed, however. It is equally important that the mast locations be representative of the terrain in which the turbines will eventually be installed. This consideration may lead to the use of more masts than the distance criteria would suggest, and it may influence their placement. For example, it is not unusual for turbines to be placed not only along the crest of a ridge where the wind is strongest, but some distance down the slope to increase the project's rated capacity. It would be beneficial in such a situation to place one or more towers off the ridgeline as well. For many projects, the mast placement has a large impact on the wind flow modeling accuracy.

Siting a tower near significant obstructions such as buildings, rock outcroppings, or isolated stands of trees can adversely affect the analysis of the site's wind characteristics (unless the proposed turbines would experience similar obstructions). Figure 3-1 illustrates the effects of an obstruction, which include reduced wind speed and increased turbulence. The zone of increased turbulence can extend up to two times the obstacle height in the upwind direction, 10 to 20 times the obstacle height in the downwind direction, and two to three times the obstacle height in the vertical direction. As a rule, if sensors must be placed near an obstruction, they should be located at a horizontal distance no closer than 20 times the height of the obstruction in the prevailing wind direction.

When placing wind monitoring systems near or within forests or extensive tree stands, it is important to consider whether the sites are typical of where turbines are likely to be located. If so, then so long as the necessary clearances (for mast installation or sodar operation, for example) are respected, there is no reason to avoid them. Nevertheless, the lowest speed sensors on the tower should be placed well above the tree canopy, if possible, to ensure an accurate measurement of wind shear. (Detailed tower instrumentation guidelines are provided in Chapter 4.)

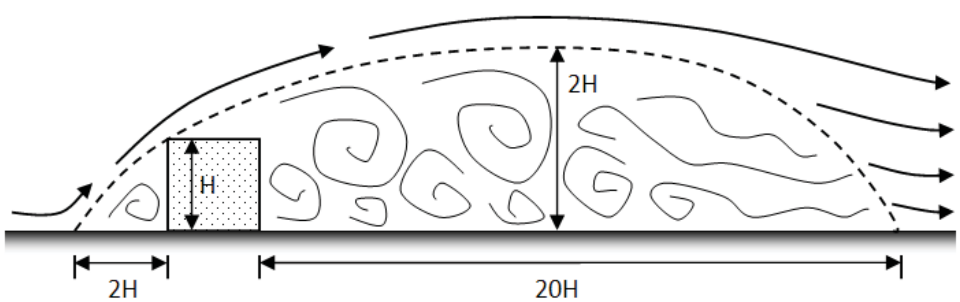


Figure 3-1 Obstruction effects on airflow.

Although recommended for some project sites (see Chapter 2), the use of very tall towers (i.e., greater than 60 m) can create significant challenges for tower placement. They include the following:

- Taller towers require a significantly larger cleared area to erect than shorter towers. In wooded areas, clearing requirements may either limit the tower height or the locations where towers can be placed.

- Taller towers often carry more instruments and therefore draw more power. Remote locations may necessitate custom-designed power-supply systems. On-site power generation from solar, wind, generators, or hybrid systems are options where AC power is not available or the best choice.
- Taller towers are more exposed to severe weather. Expected occurrences of icing, high winds, lightning, and other potentially damaging conditions must be carefully evaluated.

Existing Multi-Use Tall Towers

At first glance, existing multi-use tall towers might appear to be an appealing option for wind resource monitoring. Since no new structure is required and on-site power is usually already available, they may offer a timely and cost-effective alternative to a new, dedicated tower. Such "towers of opportunity" may also have significant drawbacks that make accurate wind resource assessment more difficult; accordingly, they are used much less frequently than dedicated towers. Important points to consider when selecting an existing tall tower for a monitoring campaign include, but are not limited to, the following:

- The tower's location relative to the wind project site and its corresponding value to the monitoring campaign
- The tower's structure (e.g., face width) and pre-existing equipment, which may disturb the airflow experienced by the anemometers
- Possible restrictions on the allowed number of instruments and their heights and boom lengths
- Costs associated with using or renting the tower
- Access to the tower and wind monitoring equipment

3.5. PERMITTING FOR WIND MONITORING

Several permits may be required before a wind monitoring tower can be installed. The amount of effort required to obtain the permits will vary depending upon the proposed tower height and location. Permitting requirements are constantly evolving, so it is recommended that the permitting process and requirements be thoroughly researched prior to installation. The following is a list of some of the agencies that can be involved in the process of securing the permits for a monitoring tower:

Federal Agencies

- Federal Aviation Administration (FAA)
- Bureau of Land Management (BLM)

State Agencies

- Department of Transportation (tower database)

Local Agencies

- Building Permit Authority

In general, a FAA permit will be needed if the tower height exceeds 200 feet (61 m). A permit may also be required if the structure is within a critical flight path or a within a certain radius of an airport. Regardless of the structure height, if the tower is on BLM land, the BLM may also require a permit to ensure that the proposed tower site is not of any cultural, ecological, or historical value.

In addition to these federal agencies, individual states, counties, and townships have their own permitting requirements for tall towers. Some states may require notification prior to installation in order to maintain an up-to-date database of tall towers. Some counties may require a Professional Engineering (PE) stamp on the structure drawings and anchoring system design or a detailed explanation of the decommissioning process to be carried out at the end of the monitoring period.

Tilt-up towers usually fall into the category of temporary structures, so permitting requirements are generally minimal. Jurisdictions normally require a standard building permit, which needs to be displayed at the site during the installation period. Building permits can be acquired from the town clerk or building inspector.

3.6. LAND LEASING

Once potential monitoring sites are identified, the developer will typically enter into an option agreement with the landowners to gain access to the land for the duration of the monitoring program and to secure rights to the land should the project go forward.

An option period typically lasts three to five years to allow sufficient time for the developer to install the mast and evaluate the wind resource. Before the term is over, the developer has the choice of either exercising an option to lease the land for a wind project, requesting an extension, or letting the option expire. This way, both the landowner's and developer's interests are protected during the option period. The developer is assured that the land will be available if the project goes forward, without having to purchase it or lease it for a long period in case it does not. The landowner is assured that if the project is not built, he or she will be able to offer the land to another developer or put it to another use.

During the option period, the developer usually pays a fee to the landowner for the right to place wind monitoring equipment on the site and sometimes to compensate for lost income and construction-related disruptions. The compensation can vary widely, depending on the wind resource, the length of the option period, the desirability of the land for wind development, and the income that may be lost from alternative uses.

In most instances, a formal option agreement is negotiated between the developer and the landowner to protect all parties. Example lease agreement terms include, but are not limited to, the following:

- **Area Leased:** The lease should clearly state where the meteorological towers can be located and the total area they will occupy. Any desired setbacks from residences and property lines should be stated.
- **Access:** The developer needs to be able to access the monitoring equipment to retrieve data and carry out repairs and maintenance; provisions in the agreement should provide the developer with such access with the landowner's consent.
- **Approved Uses:** The lease should specify what uses the landowner reserves for the land around the monitoring equipment. For instance, the landowner may reserve the right to continue to grow crops or raise cattle.
- **Crop Protection:** Typical lease provisions require developers to use their best efforts to minimize damage, and to compensate landowners for any damage that may occur. Mitigation measures covered in the lease agreement may include soil preservation or decompaction to remedy the impacts of project-related vehicle traffic.
- **Liability & Insurance:** The agreement should contain provisions to protect landowners from any liability arising from accidents. The agreement should also require that the developer carry a general liability insurance policy.
- **Term:** The duration of the option period should be clearly stated. As mentioned earlier, a typical option agreement lasts three to five years.
- **Compensation Payment Schedule:** The agreement should also outline how the landowner will be compensated and the payment schedule.

Further information about land leases, including: legal issues, compensation packages, and best practices, can be found at www.windustry.org.

Section 4

4. MONITORING STATION INSTRUMENTATION AND MEASUREMENTS

This chapter details the basic measurement parameters that are recommended for any monitoring campaign, and provides guidelines for incorporating additional parameters that may serve the campaign's objectives. The chapter also describes the instrumentation within a typical wind resource monitoring station, including its major components (sensors, tower, and data logger) as well as accessories such as power supplies, wiring, earth grounding, data storage devices, software, and communication systems. All the guidelines presented here are consistent with accepted industry standards for meteorological monitoring.

4.1. BASIC MEASUREMENTS

Meteorological instruments (sensors, probes, or monitors) are designed to monitor specific environmental parameters. This section describes the instruments and parameters for measuring wind speed, wind direction, and air temperature. Table 4-1 lists the nominal specifications for these sensors meeting the standards of wind resource assessment. A description of each parameter and appropriate monitoring heights are presented below and summarized in Table 4-2.

> ***Chapter 4 At-a-Glance***
>
> - Measurement of: (1) wind speed, (2) wind direction, and (3) air temperature is fundamental to a wind resource monitoring campaign. There are a variety of additional measurements that can be used in conjunction with these standard parameters to further characterize the conditions onsite.
> - There are several factors that need to be considered when selecting monitoring instrumentation, including the campaign's objectives for both system reliability and measurement accuracy.
> - The power requirements of the monitoring system can vary greatly depending upon the equipment being used. There are a number of power source options that can be employed (AC power, batteries, solar panels, small wind turbines, etc.).

Wind Speed

Wind speed is the most important indicator of a site's wind resource. Multiple redundant anemometers and measurement heights are therefore strongly encouraged to maximize data recovery and to accurately determine a site's wind shear. Sensor mounting recommendations are discussed further in Section 5.7: Sensor and Equipment Installation. Diagrams of typical monitoring configurations are also provided in that section.

Three anemometer types are used for the measurement of horizontal wind speed. Of these, the cup anemometer is the most popular because of its low cost and generally good accuracy. Still, both propeller and sonic anemometers are used in some settings.

Cup Anemometer. This instrument consists of a cup assembly (three or four cups) connected to a vertical rotating shaft. The wind causes the assembly to turn in a preferred direction. A transducer in the anemometer converts this rotational movement into an electrical signal, which is sent through a wire to the data logger. The logger measures the

(Source: Windsensor)

frequency (or magnitude) of the signal and applies a predetermined multiplier (slope) and offset (intercept) to convert the signal to a wind speed.

(Source: Campbell Scientific)

Propeller Anemometer. This instrument consists of a propeller (or prop) mounted on a horizontal shaft that is kept pointing into the wind by a tail vane. Like a cup anemometer, a propeller anemometer generates an electrical signal whose frequency (or magnitude) is proportional to the wind speed. This type of anemometer can record slightly lower speeds than cup anemometers under turbulent conditions. This so-called "under-speeding" is caused by the prop-vane's tendency to oscillate around the central direction or to lag behind sudden wind directional shifts, so that the propeller does not always point directly into the wind.

(Source: R.M. Young Company)

Sonic Anemometer. This instrument, which does not have any moving parts, measures the wind speed and direction by detecting variations in the speed of ultrasonic sound transmitted between fixed points within a known physical geometry. The geometry can be set up to measure wind in two or three dimensions. Because it has no rotational inertia, it is more responsive to rapid speed and direction fluctuations than cup or propeller anemometers. Sonic anemometers are usually more expensive than other types.

Specifications	Anemometer (Wind Speed)	Wind Vane (Wind Direction)	Temperature Probe
Measurement Range	0 to 50 m/s	0° to 360° (≤ 8° deadband)	-40° to 60°C
Starting Threshold	≤ 1.0 m/s	≤ 1.0 m/s	N/A
Distance Constant	≤ 3.0 m	N/A	N/A
Operating Temperature Range	-40° to 60°C	-40° to 60°C	-40° to 60°C
Operating Humidity Range	0% to 100%	0% to 100%	0% to 100%
System Error	≤ 1% (at 1σ)	5°-10°	≤ 1°C
Recording Resolution	≤ 0.1 m/s	≤ 1°	≤ 0.1°C
Lifetime (service interval)	2 years	2-6 years	2-6 years

Table 4-1 Specifications for basic sensors. (Source: AWS Truepower)

When selecting an anemometer type and model, the following factors should be considered:

- **Durability**: A wind resource monitoring campaign generally involves collecting wind data for at least a year or two. To avoid the need for frequent and costly replacements, the use of at least some anemometers capable of surviving and holding their calibration in the field for the period required is recommended. In some environments, a mixture of sensor types may be called for to achieve a balance between survivability, data recovery, and accuracy. In an extended wind monitoring program, provision should be made for the regular inspection and replacement of anemometers.

- **Operating Environment:** Not every anemometer is suited to every environment. Conditions that may cause problems include icing, heavy rain, lightning, sand and dust, extreme temperatures, and salt-water intrusion. The most common issue in North America is icing, which can cause anemometers and direction vanes to read incorrectly or stop working altogether. Heated anemometers are available from most manufacturers, and it is recommended that at least one or two be installed on every mast where significant icing is expected to minimize data loss. Heated anemometers are discussed further in Section 4.2.

- **Starting Threshold:** This is the minimum wind speed at which the anemometer starts and maintains rotation. Since low wind speeds are of no interest for wind energy generation, the starting threshold for most anemometers on the market is adequate for wind resource assessment. The exception is anemometers designed to measure vertical wind speeds, which must be sensitive to small departures (both positive and negative) from zero.

- **Distance Constant:** This is a measure of how long an anemometer takes to recover after an abrupt change in wind speed. It is defined as the distance that must be traveled by a cylinder of air passing through the anemometer for the anemometer to record 63% of an instantaneous speed change. Anemometers with relatively large distance constants may overestimate the mean wind speed in turbulent conditions compared to other anemometers. This is because they tend to respond more quickly to a rise than to a drop in speed. Sonic anemometers are not susceptible to this "over-speeding" effect. Anemometers commonly used for resource assessment have distance constants ranging from 1.8 m to 3.0 m.

- **Response to Off-Horizontal Wind:** In relatively steep terrain, the wind often has a significant vertical component. Since turbine power curves are defined according to the horizontal speed, the vertical component should either be ignored or, if necessary, removed from the measurement. Different anemometers have different characteristics in this respect. Some, particularly three-dimensional (3D) sonic anemometers, measure the horizontal and vertical wind components separately. Propeller anemometers are sensitive only to the horizontal component, just like wind turbines. Some cup anemometers (known confusingly as 3D anemometers) are sensitive to the vertical component and thus can produce a misleading estimate of the horizontal speed. Corrections can be made for these anemometers if the vertical wind speed can be measured or estimated and the anemometer's sensitivity to the inclination angle is known.[4]

[4] Papadopoulos, K.H., et al., "Effects of Turbulence and Flow Inclination on the Performance of Cup Anemometers in the Field", Boundary-Layer Meteorology Vol. 101, No. 1, 77-107.

- **Sensor Calibration:** The transfer function (slope and offset) for cup and propeller anemometers can be either a default (or consensus) function previously established by testing a large number of sensors of the same model, or it can be one measured specifically for the sensor that was purchased. In the latter case, the sensor is said to be calibrated. Either approach may be acceptable depending on the circumstances. There is evidence that for NRG #40 cup anemometers, in particular, the accepted consensus function produces results that match anemometers used for power performance testing more closely than do measured transfer functions.[5, 6] An advantage of using calibrated sensors - whether the measured transfer function is used or not - is that there is greater assurance that "bad" sensors will be discovered before they are installed in the field. In addition, with calibrated sensors it is possible to determine the change in sensor response over the course of the monitoring period by removing it at the end and testing it again. High-quality, undamaged anemometers should exhibit very little change.

There are many industry-accepted cup anemometers used in wind resource measurement campaigns. A list of wind resource assessment sensors is provided in Appendix A. Although each of the recommended sensor models meets wind-industry standards, it may be desirable to deploy more than one model on each mast. This strategy can reduce the risk of data losses or measurement errors caused by problems affecting just one model. Some anemometers have been classified according to the standards outlined by institutions like MEASNET or the International Electrotechnical Commission (IEC)[7]. The performance of these anemometers complies with the institution's specifications for high-accuracy applications such as power curve testing. Still, it is usually unnecessary for every anemometer on a mast to meet this standard.

Wind Direction

(Source: NRG Systems, Inc)

Wind direction measurements are a necessary ingredient for modeling the spatial distribution of the wind resource across a project area and for optimizing the layout of the wind turbines. A wind vane is usually used to measure wind direction. (With prop-vane sensors, no separate vane is required.) In the most familiar type, a horizontal tail connected to a vertical shaft rotates to align with the wind. To define the wind direction with adequate redundancy, it is recommended that wind vanes be installed on at least two monitoring levels. Ideally, they should not be mounted on the same booms or even at the same heights as the anemometers as they could interfere with obtaining accurate speed readings. It is customary to mount the direction vanes one or two meters below the anemometers.

[5] Hale, E. "Memorandum: NRG #40 Transfer Function Validation and Recommendation." AWS Truewind. 8 January 2010.
[6] Young, M; Babij, N., "Field Measurements Comparing the Riso P2546A Anemometer to the NRG #40 Anemometer" Global Energy Concepts, 2007
[7] The IEC standard on power performance measurements (IEC 61400-12-1) classifies cup anemometers based upon sensor accuracy. It should be noted that this document requires that turbine performance tests be carried out with calibrated Class I anemometers, and that the measured calibration constants be used.

For a wind vane with a potentiometer-type transducer, the data logger usually provides a voltage across the potentiometer's entire resistive element and measures the voltage where the potentiometer's wiper arm makes contact. The ratio between these two voltages determines the position of the vane with respect to its reference direction. Since the potentiometer cannot cover a full 360°, a small gap is left between where it starts and ends. In this so-called deadband, the output signal is random and the direction cannot be determined. The best practice is to orient the deadband directly facing the tower if the vane's supporting horizontal boom arm points into the prevailing wind direction; in addition, the size of the deadband should not exceed 8°. The precision of the wind vane direction is another important consideration. A resolution better than or equal to 1° is recommended.

Air Temperature

Air temperature is an important characteristic of a wind farm's operating environment. It is normally measured either 2 m to 3 m above ground level, near hub height, or both. In most locations the average air temperature near ground level is within 1°C of the average at hub height. Air temperature is used to estimate air density, which affects the calculation of power production. The air temperature readings are also used in the data validation process to look for icing events.

(Source: R.M. Young Company)

An ambient air temperature sensor is typically composed of three parts: the transducer, an interface device, and a radiation shield. The transducer contains a material (usually nickel or platinum) exhibiting a known relationship between resistance and temperature. Thermistors, resistance thermal detectors (RTDs), and temperature-sensitive semiconductors are common element types. The resistance value is measured by the data logger (or interface device), which then calculates the air temperature based on the known relationship. The temperature transducer is housed within a radiation shield to prevent it from being warmed by sunlight.

Measurement Parameters	Example Heights (60m tubular tower)	Example Heights (83m lattice tower)
Wind Speed (m/s)	57.2 m, 47.4 m, 32.0 m	80 m, 60 m, 40 m
Wind Direction (°)	53.5 m, 43.7 m	80 m, 60 m, 40 m
Temperature (°C)	3 m	3 m and/or hub height

Table 4-2 Basic measurement parameters.

4.2. ADDITIONAL MEASUREMENTS

Depending on the site conditions and the needs and priorities of the monitoring program, additional sensors may be included for vertical wind speed, high-accuracy temperature, relative humidity, barometric pressure, and solar radiation. Table 4-3 lists the nominal specifications for these sensors; the measurement parameters associated with each sensor are summarized in Table 4-4. Bear in mind that each additional instrument requires power, and there are limits to the number of instrument channels supported by data loggers.

Specification	Pyranometer (Solar Radiation)	Vertical Propeller Anemometer	High-Accuracy Temperature (ΔT)	Barometer (Atmospheric Pressure)
Measurement Range	0 to 1500 W/m^2	-50 to 50 m/s	-40 to 60°C	94 to 106 kPa (sea level equivalent)
Starting Threshold	N/A	≤ 1.0 m/s	N/A	N/A
Distance Constance	N/A	≤ 4.0 m	N/A	N/A
Operating Temperature Range	-40 to 60°C	-40 to 60°C	-40 to 60°C	-40 to 60°C
Operating Humidity Range	0 to 100%	0 to 100%	0 to 100%	0 to 100%
System Accuracy	≤ 5%	≤ 3%	≤ 0.1°C	≤ 1 kPa
Recording Resolution	≤ 1 W/m^2	≤ 0.1 m/s	≤ 0.01°C	≤ 0.2 kPa

Table 4-3 Specifications for optional sensors. (Source: AWS Truepower)

<u>Vertical Anemometer</u>

In complex terrain (defined by the IEC as having a slope of more than 10 percent within a distance of 20 times the hub height from turbines[8]), it is recommended that anemometers capable of measuring the vertical wind speed be used in conjunction with standard instruments. By directly measuring the vertical component of the wind, the energy-producing horizontal component can be better estimated. In addition, vertical wind speed measurements can be an important input for turbine loading and suitability calculations, as severe or frequent off-horizontal winds can cause damaging loads and wear.

(Source: R.M. Young Company)

Two common approaches for measuring the vertical wind speed are to mount a propeller anemometer with its axis pointed vertically and to use a sonic 3D anemometer. Whichever approach is taken, since vertical winds can vary greatly with height above ground, it is recommended that the anemometer be placed as close to hub-height as possible without causing interference with other sensors. (A vertical separation of one to two meters between sensors is usually adequate.)

Since vertical motions are often very small, an anemometer of unusual sensitivity is required. A propeller anemometer requires a transducer that can indicate both upward and downward motion. The signal is usually a DC voltage whose sign and magnitude are interpreted by the data logger (or an interface device). Sonic sensors are more expensive, but offer the advantage of measuring both vertical and horizontal wind components simultaneously.

[8] IEC 61400-12-1 First Edition (2005-12)

Heated Wind Sensors

The buildup of ice on anemometers can cause the sensor to rotate slower, stop, or even break due to loading (e.g. falling ice). Likewise, the accumulation of ice on wind vanes can cause the sensor to be off balance or alter its aerodynamic profile, distorting the directional readings, or can freeze it in position. For these reasons, where frequent or heavy icing is expected, it is recommended that met towers be equipped with at least one or two heated anemometers and direction vanes. Nevertheless, heated sensors consume much more power than unheated sensors; accordingly, towers equipped with heated sensors need access to power. (Power supply options are discussed in Section 4.8.)

Except during periods of icing, heated sensors are generally less accurate than unheated sensors. Therefore, it is recommended that unheated sensors be the primary source of wind data, while heated sensors be used only to fill gaps in the primary data record. In addition, in order to maintain as much consistency as possible in the heated-anemometer readings, it is recommended that power be applied to the heating elements throughout the year, not just in the cold season. In a typical configuration, an unheated anemometer might be paired with a heated anemometer on each of the top two levels of the mast, and one of the two direction vanes on the mast might be heated. This approach strikes a balance between high overall data recovery and good measurement accuracy.

Delta-Temperature Sensors

The parameter ΔT (pronounced delta-tee) is the difference in temperature between two heights and is a measure of atmospheric stability or buoyancy. The challenge is to measure the temperature difference with sufficient accuracy to be useful. According to the EPA Quality Assurance Handbook (1989), the maximum allowable ΔT error is 0.003 C/m (degrees Celsius per meter of height). With heights of 10 m and 40 m, the allowable error is just 0.1°C. To achieve this, a pair of identical temperature sensing subsystems calibrated and matched by the manufacturer can be used. One sensor needs to be placed approximately 3 m above the ground, and the other a short distance (e.g. 2 m) below the top sensing level on the tower. In addition, both sensors need to be mounted and shielded in the same manner so they respond similarly to ambient conditions. To further reduce errors, a radiation shield that uses either forced (mechanical) or natural (passive) aspiration is required. (To meet EPA guidelines, forced aspiration may be required.) The data logger manufacturer should be consulted to determine compatible sensor types and models.

Barometric Pressure Sensors

Barometric pressure is used with air temperature to determine air density. Normal variations in pressure at the same temperature can affect air density by about 1%. Barometric pressure is difficult to measure accurately in windy environments because of the dynamic pressures induced when wind flows across an instrument enclosure. High-quality instruments are therefore quite expensive. As a result, most resource assessment programs do not measure barometric pressure and instead either rely on temperature and elevation alone or adjust pressure readings from a regional weather station. Under most conditions, both methods can yield acceptable accuracy.

For projects at especially high elevations (such as greater than 2000 m above sea level) and with no nearby weather station at a similar altitude, it is recommended that high-accuracy air pressure measurements be made to decrease the uncertainty in air density.

Several barometric pressure sensors, or barometers, are commercially available. Most models use a piezoelectric transducer that sends a DC voltage to a data logger, and may require an external power source. Consult with the data logger manufacturer to determine a compatible sensor model. Note that the transducer needs to be exposed to the ambient outside air pressure. It must not be mounted in an airtight enclosure, or in a way that wind flow around the inlet could induce pressure changes.

(Source: Campbell Scientific)

Relative Humidity

The use of a relative humidity sensor can improve the accuracy of air density estimates. The addition of water vapor to air reduces its density; thereby decreasing the wind's kinetic energy. Still, the potential influence of relative humidity on energy prediction is negligible.

Global Solar Radiation

The solar energy resource can be measured as part of a wind monitoring program. Solar radiation, when used in conjunction with wind speed and time of day, can also be an indicator of atmospheric stability. A pyranometer is used to measure global horizontal (total) solar radiation, which is the combination of direct sunlight and diffuse sky radiation striking a horizontal plane. One common type of pyranometer uses a photodiode, which generates a very small current proportional to the amount of incident sunlight (called insolation). Another type uses a thermopile, a group of thermal sensors, which produces a very small voltage. The data logger (or a supplementary interface device) applies a predetermined multiplier and offset to calculate the global solar radiation reading. Since the output signal from the sensor is usually very small (microamps or microvolts), it may have to be amplified to be read by the logger.

Measurement Parameters	Typical Monitoring Heights
Vertical Wind Speed (m/s)	2m below upper sensor level
Delta Temperature (°C)	3m, 2m below upper sensing level
Barometric Pressure (kPa)	2-3m
Relative Humidity (%)	3m or 2m below upper sensor level
Solar Radiation (W/m^2)	3-4m

Table 4-4 Optional measurement parameters.

The pyranometer must be level to measure global horizontal solar radiation accurately. When installed off a tower in the northern hemisphere, it is best to locate the sensor on a boom extending southward, above or beyond any obstructions to minimize shading from other instruments and the tower. The recommended measurement height is 3-4 m above ground. Pyranometers may require frequent maintenance visits for cleaning and re-leveling.

4.3. RECORDED PARAMETERS AND SAMPLING INTERVALS

It is recommended that the parameters to be measured and their sampling and recording intervals be consistent with those typically used in the wind industry. Adherence to these standards will facilitate analysis as well as review by third parties. The industry-standard recording interval is 10 minutes, though occasionally other (usually shorter) intervals may be used. The parameters are generally sampled once every one or two seconds (depending on the logger model) within each interval. (The sampling frequency should not be greater than the pulse frequency from the anemometer to avoid oversampling errors.) The data are recorded as averages, with standard deviations and maximum and minimum values, depending on the parameter. Data recording should be serial and all records marked by a time and date stamp. These requirements are all standard functions of data loggers designed for wind energy applications.

The recorded values will be the basis for the data validation procedures described in Chapter 9. Each is presented below and summarized in Table 4-5.

Measurement Parameters	Recorded Values
Wind Speed (m/s)	Average Standard Deviation Min/Max
Wind Direction (degrees)	Average Standard Deviation Max Gust Direction
Temperature (°C)	Average Min/Max
Solar Radiation (W/m^2)	Average Min/Max
Vertical Wind Speed (m/s)	Average Standard Deviation Min/Max
Barometric Pressure (kPa)	Average Min/Max
Delta Temperature (°C)	Average Min/Max
Relative Humidity (%)	Average Min/Max

Table 4-5 Basic and optional parameters.

Average

The average or mean value in each ten-minute interval is recorded for all parameters except wind direction. For wind direction, the average is defined as a vector resultant value, which is the direction implied by the means of the northerly and easterly speeds. Averages are used in reporting wind speed variability as well as wind speed and direction frequency distributions.

4.4. STANDARD DEVIATION

The standard deviation should be determined for both wind speed and wind direction and is defined as the population standard deviation (σ) for all one- or two-second samples within each ten-minute interval. The standard deviations of wind speed and wind direction are indicators of turbulence. They are also useful for detecting suspect or erroneous data.

Maximum and Minimum

The maximum and minimum values observed during each interval should be recorded for all parameters. If possible, the coincident directions corresponding to the maximum and minimum wind speeds should also be recorded. An additional parameter that may be desirable but is not available on all logger models is the maximum two- or three-second gust, which can affect whether a given wind turbine model is deemed suitable for the site.

4.5. DATA LOGGERS

Data loggers (or data recorders) have evolved from strip chart recorders read by a human operator to a variety of digital stand-alone devices. Many manufacturers now offer complete data-logging systems that include integrated data storage and transfer options.

All data loggers store data locally, and many can transfer the data to another location through cellular telephone, radiofrequency telemetry, or satellite link. Remote data transfer allows the user to obtain and inspect data without making frequent site visits and also to verify that the logger is operating correctly. Section 4.7 provides detailed information on data transfer equipment options.

(Source: Campbell Scientific)

The data logger must be compatible with the sensor types employed and be able to support the desired number of sensors, measurement parameters, and sampling and recording intervals. It is prudent to mount the logger in a noncorrosive, water-tight, lockable enclosure to protect it and peripheral equipment from the environment, theft, and vandalism. It is recommended that the data logger also:

- Be capable of storing data values in a sequential format with corresponding time and date stamps
- Contribute negligible errors to the signals received from the sensors
- Have an internal data storage capacity of at least 40 days
- Possess an onboard real-time clock so that the time stamps will remain accurate even if the logger loses power
- Operate in the same environmental extremes as those listed in Table 4-1
- Offer retrievable data storage media when a remote uplink is not possible
- Offer remote data collection options
- Operate on battery power (which may be augmented by other sources such as a solar panel)
- Offer non-volatile memory storage so that data are not lost if power fails.

A number of electronic data loggers that meet these criteria are commercially available, a vendor's list is provided in Appendix A.

4.6. DATA STORAGE DEVICES

Every data logger contains a computer running on operating system software. It includes a small data buffer to temporarily hold data for processing. The computer accesses this buffer to calculate the desired parameters, such as means and standard deviations. The resulting data values are then stored in memory. Some data loggers have a fixed, or firm, operating system that cannot be altered, or can be only slightly modified; others are user-interactive and can be reprogrammed for different tasks. In older models, the operating system and data buffers are sometimes stored in volatile memory. Their drawback is that they need a continuous power source to retain data. Data loggers that incorporate internal backup batteries or use non-volatile memory are preferred because data are less likely to be lost.

Data Processing and Storage

Data processing and storage methods vary according to the data logger. A basic understanding of how the logger processes data is important to ensure data are protected (refer to Chapter 7). There are two commonly used formats for recording and storing data: ring memory and fill and stop.

- **Ring Memory:** In this format, data archiving is continuous, but once the available memory is filled to capacity, the newest data record is written over the oldest.
- **Fill and Stop Memory:** In this configuration, once the memory is filled to capacity, no additional data are archived. This stops the data logging.

In the past, the ring memory format was preferred over fill and stop memory because it allowed data logging to continue if the operator was unable to retrieve the data before the memory buffer filled. Given the memory storage capacity of modern data loggers, this is of much less concern. Today's memory buffers are typically able to store at least 6-12 months of data, unless the recording interval is much less than the usual 10 minutes.

Storage Devices

Most manufacturers offer several options for data storage devices. The most common are presented in Table 4-6 below.

Storage Device	Description	Download Method/ Needs
Memory Card	Independent memory chips in numerous formats (e.g., MMC, SD, microSD, SDHC, memory Stick, USB flash drive) used in cameras and other devices.	Read and erased onsite or replaced. Reading device and software required.
Solid State Module	Integrated electronic device that directly interfaces with the data logger.	Read and erased onsite or replaced. Reading device and software required.
Data Card	Programmable read write device that plugs into a special data logger socket.	Read and erased on-site or replaced. Reading device and software required.
EEPROM Data Chip	An integrated circuit chip incorporating an electrically erasable and programmable read-only memory device.	EEPROM reading device and software required.
Magnetic Media	Familiar floppy disk or magnetic tape (i.e., cassette).	Software required to read data from the media.
Portable Computer	Laptop or notebook type computer.	Special cabling, interface device, and/or software may be required.

Table 4-6 Data storage devices.

4.7. DATA TRANSFER EQUIPMENT

The selection of a data transfer and handling process and data logger model depends on the monitoring program's resources and requirements. As a rule, the manufacturer should be consulted to ensure compatibility between system components. It is recommended that a test unit be purchased for in-house testing prior to committing to a new monitoring system configuration.

Data are typically retrieved and transferred to a computer either manually or remotely.

Manual Data Transfer

Manual retrieval requires visiting the site to transfer data. Typically this involves two steps:

(1) The current storage device (e.g., data card) is removed and replaced and sent to another location for download. Alternatively, the data can be transferred directly to a laptop computer. Many loggers use an RS-232 serial port to interface with a computer. Computers that do not have an RS-232 port can use a USB port and USB/RS-232 adapter.

(2) The collected data are transferred to a central computer where the data are analyzed and backed up.

The advantage of the manual method is that it allows for visual inspection of the equipment. Disadvantages include additional data handling steps, which increase the risk of data loss, and the need for frequent site visits to minimize the amount of data that might be lost if a sensor or the logger malfunctions between visits.

Remote Data Transfer

Remote transfer requires a telecommunications link between the data logger and the central computer. The communications system may incorporate direct-wire cabling, modems, phone lines, cellular phone equipment, radio frequency (RF), telemetry equipment, satellite-based telemetry, or for redundancy, a combination of these components. The main advantage of this method is that the data can be retrieved and inspected more frequently (e.g., weekly) than may be practical with site visits. This means that problems with the equipment can be more quickly identified and resolved, thus reducing data losses and improving data recovery. Many logger manufacturers now offer integral remote data collection equipment. The main disadvantage of the remote method is the cost of the equipment. In addition, some sites have poor cellular coverage, and other telecommunications options can be expensive.

There are two methods of remote data retrieval: those initiated by the user (call out), and those initiated by the logger (phone home). The first type requires the user to oversee the telecommunication operation. Steps include initiating the call to the in-field data logger, downloading the data, verifying data transfer, and erasing the logger memory. Some call-out data logger models are compatible with computer-based terminal emulation software packages with batch calling. Batch calling automates the data transfer process, allowing the user to download data from a number of monitoring sites at prescribed intervals. Batch programs can also be written to include data verification routines. The data logger manufacturer should be consulted to determine the compatibility of its equipment with this feature.

The phone-home data logger automatically calls the central computer at prescribed times to transfer data. In the past, the phone-home method could not be used to support as many towers as the call-out method, because call times had to be spaced far apart to allow for slow or repeated transfer attempts. The newest generation of data loggers uses the internet to send data out as attached email files. This allows for concurrent data transfer from multiple sites. In addition, the data can be downloaded to more than one computer, providing greater data security and convenience.

Data loggers with remote data transfer via cellular communications are gaining popularity because of their ease of use and reasonable cost. The cellular signal strength and type (GSM or CDMA) at the site should be determined in advance; this can be done with a portable phone. Where the signal strength is weak, an antenna with higher gain can sometimes be successful. Failing that, a satellite modem linking into the Globalstar or Iridium global network is an option.

Guidelines for establishing a cellular account are usually provided by the data logger supplier. It is important to work closely with the equipment supplier and cellular telephone companies to resolve any questions before monitoring begins. It is best to schedule data transfers during off-peak hours to take advantage of discounted rates.

4.8. POWER SOURCES

All electronic data loggers require a power source sized to meet the total power requirements of the system. The leading power options are described below.

Household Batteries

The newest generation of loggers employ low-power electronic components whose operation can be sustained by common household batteries (D cells, 9-volt, and others) for six months to a year. Although the systems are generally reliable, if the batteries fail data will be lost. In addition, the power is not sufficient for towers with heated sensors or other special power needs. To address these issues, the loggers' batteries are often augmented by another power source.

Solar-Battery Systems

For more reliable long-term operation as well as for meeting larger power needs, the most common choice is a rechargeable lead-acid battery coupled to a solar panel. Packaged solar-battery systems are offered by most logger vendors for this purpose.

Lead-acid batteries are a good choice because they can withstand repeated discharge and recharge cycles without significantly affecting their energy storage capacity, and they can hold a charge well in cold temperatures. Caution should always be used when working with large batteries like these to avoid a short circuit between the battery terminals. It is also recommended that newer battery designs that encapsulate the acid into a gel or paste to prevent spills, called non-spillable or gel batteries, be used. Although long-lived, lead-acid batteries subjected to many charge and discharge cycles eventually lose capacity. It is important to take this decline into account when sizing the battery if it is intended to last in the field for several years.

The solar panel must be large enough to operate the monitoring system and keep the battery charged during the worst expected conditions (usually in winter). To avoid outages that may cause data loss, it is recommended that the solar and storage system be designed for at least seven days of autonomous operation (without recharging). The solar system must also be reverse-bias-protected with a diode to prevent power drain from the battery at night. In addition, it must include a voltage regulator to supply a voltage compatible with the battery and to prevent overcharging during months with the most sunlight. Logger vendors offering solar-battery packages can advise on the proper size for any location.

AC Power

Alternating Current (AC) power is not normally required for wind monitoring systems. Moreover it is unusual (except for communications towers) for a met mast to be close enough to a source of AC power to make connecting to it worthwhile. Nevertheless, where AC power is conveniently at hand, the instrumentation loads are unusually large, or solar panels are not practical, then AC power can be the right choice. It should be used only to trickle-charge a storage battery, not to power the logger directly. A surge/spike suppression device should be installed to protect the system from electrical transients. In addition, all systems must be properly tied to a common earth ground (see Section 5.7).

Other Power Options

Other power sources that may be used in some circumstances include small wind systems, wind/solar hybrid systems, and diesel generators. Small wind and wind/solar hybrid systems can be a good choice where there is plenty of wind and solar radiation is limited (arctic environments, for example), or where solar panels are likely to be blocked by trees or other obstacles much of the time. Diesel generators require costly refueling, but there are sites where it can be a practical option.

4.9. TOWERS AND SENSOR SUPPORT HARDWARE

Towers

There are two basic tower types: tubular and lattice. For both types, three versions are available: tilt-up, telescoping, and fixed. Except for the self-supporting lattice tower, all use guy cables to stabilize the tower. For most new sites, tubular, tilt-up towers are recommended because they are relatively easy to install (the tower can be assembled and sensors mounted and serviced at ground level), they require minimal ground preparation, and they are relatively inexpensive. The main exception is where tall towers (more than 60 m high) are required.

Towers should be strong enough to withstand the extremes of wind and ice loading expected for the location, as well as stable enough to resist wind-induced vibration. Note that some US counties have their own design requirements for wind and ice loading that can have implications for the permitting process. In coastal environments, resistance to salt water exposure is important. Guy wires should be secured with anchors that match the site's soil conditions (the vendor and installer should advise), and all ground-level components should be clearly marked to prevent accidents. Protection from lightning (including lightning rod, cable, and grounding rod) is a must. In some locations, security measures to prevent vandalism, theft, and unauthorized climbing may be required; likewise protections against cattle or other large animals. Offshore met instrument installations require specialized equipment.

Sensor Support Hardware

The sensor support hardware includes the masts (vertical extensions) and mounting booms (horizontal extensions). Both must position the sensor away from the support tower to minimize any influence by the tower and the mounting hardware on the measured parameter. In order to keep tower effects small, the following guidelines are recommended for anemometers and vanes:

- Locate sensors at least seven tower diameters from tubular towers
- Locate sensors at least 3.75 times the tower face width from lattice towers
- Locate the topmost sensors at least 10 tower diameters below the top of the tower
- Locate sensors at least 12 times the boom diameter above the boom arm

It is advisable to use sensor support hardware that is able to withstand the same wind and ice loading extremes as the tower, and not be prone to wind-induced vibration. The hardware should be protected against corrosion, especially in costal environments. Drainage holes in sensor housings need to be kept open to prevent water accumulation and expansion in freezing conditions. Tubular (hollow) sensor masts should be used instead of solid stock material.

4.10. WIRING

The following are guidelines for selecting the proper electrical wire or cable type:

- Use the proper class wire for the voltage
    - The wire class requirements will be sensor-specific; in general, sensor manufacturers offer compatible sensor cables.
- Use wire with an ultraviolet (UV) resistant insulating jacket
- Use insulation and conductor types that are flexible over the full temperature range expected at the site
- Use shielded and/or twisted-pair cables. Both prevent ambient electrical noise from affecting measurements. Normal practice is to tie only one end of a shielded cable's drain wire to earth ground.

4.11. MEASUREMENT SYSTEM ACCURACY AND RELIABILITY

Manufacturers use various definitions and methods to express their product's accuracy and reliability. This section provides the basic information needed to select the proper equipment and meet the specifications cited in Table 4-1.

Accuracy

The accuracy of any system tends to be dominated by its least accurate component. For most measurements, that is the sensor itself. Errors associated with the electronic subsystem (data logger, signal conditioner, and associated wiring and connectors) are typically negligible.

The system error of an instrument is defined as the standard deviation of errors observed for a large number of instruments of that type, under controlled conditions, with respect to an accepted standard. For a given instrument, the measured value should be within the quoted system error of the true value with 68% confidence, and within twice the system error of the true value with 95% confidence. The system error applies only to controlled conditions; factors that may arise in the field, such as tower influences on the free-stream wind speed, are not considered.

Not all manufacturers express system error in a consistent format. The error is typically expressed in one of three ways:

- As a difference (as in, for temperature, ≤1 ° C), calculated as

$$[Measured\ Value\ -\ Accepted\ Standard\ Value]$$

- A difference stated as a percentage of the accepted standard value (as in, for wind speed, ≤3%), calculated as

$$\left[\frac{Measured\ Value -\ Accepted\ Standard\ Value}{Accepted\ Standard\ Value}\right](100)$$

- An agreement ratio stated as a percentage of the accepted standard value (as in, 95% accuracy), calculated as

$$\left[\frac{Measured\ Value}{Accepted\ Standard\ Value}\right](100)$$

Accuracy is often confused with precision. System precision (sometimes also expressed in terms of a standard deviation) refers to the consistency of repeated values recorded by the same instrument under the same conditions. Precision may also refer to the number of digits reported by the data logger. To avoid rounding errors in subsequent analysis, it is recommended that values be recorded to one significant digit greater than the nominal precision.

Reliability

System reliability is the measure of a system's ability to constantly provide valid data. Vendors usually test the reliability of their equipment to determine the product's life cycle. They will often cite a mean time between failures under certain conditions. In general, the best indication of a product's reliability is the experience of other users. The vendor can be asked for references. Other users can be contacted at conferences and workshops. Comprehensive quality assurance procedures and redundant sensors are important ways to maintain high system reliability.

Section 5

5. INSTALLATION OF MONITORING STATIONS

The installation phase of the monitoring program can proceed once the site selection and wind monitoring system design have been completed, all required permits have been obtained, and the necessary equipment has been acquired. This chapter provides guidelines on key installation steps, including equipment procurement, inspection and preparation, tower installation, sensor and equipment installation, site commissioning, and documentation.

> ***Chapter 5 At-a-Glance***
>
> - Before installation, the monitoring equipment should be thoroughly inspected and tested.
> - The installation of a meteorological tower requires careful planning, adherence to safety protocol, and sound judgment.
> - Sensors should be mounted in a manner that minimizes the influence on the readings of the tower, mounting hardware, other equipment, and other sensors.
> - A complete and detailed record of the site characteristics and sensor information should be maintained for every monitoring station.

5.1. EQUIPMENT PROCUREMENT

The first step in the process is to procure the equipment that will be needed to meet the objectives of the wind monitoring program, as defined in the measurement plan. This process often involves tradeoffs between cost, convenience, and performance. At this early stage of project development, budgets can be tight, leading to a desire to economize in equipment procurement. While cost is an important consideration at all times, a monitoring program that is designed with cost as a paramount concern could be unsuccessful.

The procurement process typically begins with the definition of the number of towers, the tower types and heights, the desired measurement parameters and heights, and the desired data sampling and recording intervals. The program manager can then move on to define the sensor types and quantities (including spares), the required mounting booms, cables, and hardware for each sensor, the data logger processing requirements and number and types of data channels required (which may affect the choice of logger model and manufacturer), and the data retrieval method (manual or remote). Along the way, normal and extreme weather conditions for the sites should be investigated to ensure that the specified equipment will perform reliably throughout the year.

Finally, price quotes for equipment packages meeting the program's objectives should be obtained, along with information on warranties, product support, and delivery dates, and compared between suppliers. A manufacturer that provides comprehensive product support can be invaluable resource when installing and troubleshooting the operation of a monitoring system; some even offer training courses. A list of equipment vendors is provided in Appendix A.

5.2. EQUIPMENT ACCEPTANCE TESTING AND FIELD PREPARATION

Acceptance Testing

Once the equipment arrives, it is advisable to check it immediately for broken or missing parts, and all system components should be thoroughly inspected and tested. The inspection findings should be documented, and components that do not meet specifications should be returned immediately to the manufacturer for replacement. The following acceptance testing procedures are recommended:

Data Logger

- Ground the logger before connecting sensors to prevent potential damage from electrostatic discharge.
- Turn on the data logger and check the various system voltages.
- If applicable, set up and activate the telecommunications account (cellular or satellite-based) and email services following the manufacturer's instructions.
- First connect the drain wire, then connect all sensors to data logger terminals with the shielded cabling to be used.
- Verify that all sensor inputs are operational.
- Verify the logger's data collection and data transfer processes.

Here is a simple test scenario: Following the manufacturer's instructions, connect a sensor to the data logger and collect a sample of data at one-minute (or higher) frequency averaging interval. Transfer the recorded data from the storage device (e.g., data card) to a computer using the logger's data management software. View the data and ensure that (a) the data logger is functioning; (b) the data transfer was successful; (c) the storage device is functioning; and (d) the reported values are reasonable. Repeat the above steps using remote transfer, if required.

Anemometers and Wind Vanes

- If calibrated anemometers were purchased, consult each calibration certificate to ensure the sensor behavior is within normal bounds.
- Inspect each anemometer and vane to ensure that it spins freely through a full rotation. Check for unusual friction and listen for binding or dragging components.
- Using the shielded cabling and following the manufacturer's instructions, connect each sensor to the correct data logger terminal. Verify the reasonableness of each sensor output as displayed by the data logger. For the anemometers, verify both a zero and non-zero value by holding and then spinning the cups or propeller. For the wind vanes, verify the values at the four cardinal points: north, south, east, and west.

Temperature Sensor

- Perform a single point calibration check at room temperature; once stabilized, compare the sensor temperature readings to a known calibrated thermometer if available. Deviations between sensors should not exceed 1°C.

Solar Panel Power Supply

- Place in direct sunlight and confirm the output voltage. Note that polarity is important when connecting to the terminals of some loggers.

Mounting Hardware

- Inspect the sensor mounting booms to ensure they are rugged and durable.
- Inspect any welds or joints for soundness.
- Preassemble one mount for each type of sensor to confirm all parts are available.

Field Preparation Procedures

Thorough preparation before going into the field to install equipment can save precious time and reduces the risk of problems requiring a costly return visit.

- Assign designation numbers to each monitoring site and clearly mark equipment destined for each site.
- Enter all pertinent site and sensor information on a Site Information Log (refer to Section 5.9).
- Install the data logger's data management software on a personal computer and enter the required information.
- If desired, program the data logger in advance with the appropriate site and sensor information (slopes and offsets). Enter the correct date and time in the data logger.
- Insert the data logger's data storage card or other storage device.
- To save valuable field installation time, assemble as many components in-house as possible. For example, sensors can be pre-wired and mounted on their booms.
- Some sensors are fragile, so properly package all equipment for safe transport to the field.
- Pack all tools that will be needed in the field.
- Include at least one spare of each component, when practical. The number of spares depends on the amount of wear the equipment is expected to endure, as well as the expected lead time to obtain a replacement. The cost of the spare equipment should be weighed against the time and effort to quickly find a replacement should the need arise.

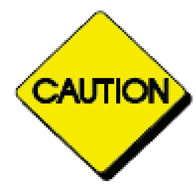
5.3. INSTALLATION TEAM

The quality of the data collected in a wind monitoring program depends on the quality of the installation. The installation team should have experienced personnel, one of whom is clearly assigned a supervisory role. This will promote efficiency and safety. The team should also have an appropriate number of personnel for the type of tower and equipment to be installed. The installation of a 50 m or 60 m tilt-up tubular tower requires a crew of at least five people. Labor requirements for installing lattice towers vary, and need to be determined by a qualified engineer.

The personnel responsible for the site's selection may not always be involved in the installation. If this is the case, it is important that the installation team leader obtain all pertinent site information, including the latitude and longitude (verifiable with a GPS receiver), local magnetic declination, prevailing wind direction, and road maps, as well as topographic maps and site photographs that precisely show the planned tower location.

5.4. SAFETY

Tower installations are inherently dangerous. Towers and equipment can fall on people, climbers can fall from towers, and if AC power is involved or there are nearby power lines, there is a risk of electrocution. In some remote areas, even wildlife may pose a hazard. It is essential that the team leader strictly enforce safety protocols. In addition, having experienced staff, following manufacturers' recommendations, and taking common-sense precautions will reduce risks.



The team should:

- Be trained in and abide by all applicable safety procedures (e.g. OSHA, developer's safety protocol).
- Remain in communication with each other and with the home office.
- Follow all safety guidelines provided by the tower and equipment manufacturer.
- Use common sense during the installation process. For example, if there is lightning activity, postpone work until the danger has passed.
- Have the proper safety equipment, including hard hats, protective gloves, eye protection, vests for greater visibility, a first aid kit, and if tower climbing is required, certified climbing harnesses and lanyards as well as proper shoes or boots.
- Maintain adequate hydration, use sunscreen, and wear appropriate cold-weather clothes where necessary
- Be trained in first aid and CPR
- Make sure the base of the tower is at least one and a half tower heights away from overhead power lines.
- Be aware of any equipment on the tower that may be electrically live, and if possible, turn off AC power at the tower base before working on the tower.

- Before digging or installing earth anchors or rods, contact the local underground facilities protection organization to identify and mark any existing hazards (e.g., buried electric or gas lines).
- Inspect any existing tower, anchors, and guy cables before conducting new work.
- Tension guy wires according to the tower manufacturer's specifications.
- For lattice tower installations, ensure that at least two tower climbers are present, both trained in tower rescues.
- Notify local airfields when new towers are erected to ensure that the pilots are aware of the new structure, and ensure the towers are marked in accordance with local guidelines.

5.5. DETERMINATION OF TRUE NORTH

Knowing the direction of true north is essential for interpreting direction data, and is also useful during the tower layout and installation. In surprisingly many monitoring programs, direction vanes and anemometers are not oriented in the correct, or documented, direction. This can cause significant errors in wind flow and wake modeling and result in a poor turbine layout.

Often, directional errors arise because of confusion between magnetic and true north. Magnetic north is what a magnetic compass reads; true north is the direction along the local line of longitude to the north pole. Sometimes the correction from magnetic to true north is applied wrongly, and sometimes it is applied twice, once in the field, once by the data analyst. When tower installers use a magnetic compass, the risk of error can be reduced by instructing them to orient the sensors with respect to magnetic north, and by correcting the readings to true north when the data are analyzed. Fortunately, these days, most GPS receivers can indicate true north, thus eliminating the need to consider magnetic north at all.

If a correction from magnetic north is required, the local magnetic declination (in degrees) must be established. This correction can be found on topographic or isogonics maps of the area (an example is provided in Figure 5-1). How the correction is applied depends on whether the site is east or west of the longitude of the magnetic north pole. To the east, the declination is expressed in degrees west of true north, and the bearing toward true north therefore equals the declination. To the west, the true north bearing is 360° minus the declination. In both cases the true north bearing must be added to the direction relative to magnetic north to obtain the direction relative to true north. For example, suppose a sensor boom has an orientation of 150° from magnetic north. If the local magnetic declination is 15°W, then the boom orientation from true north is 135°. If, however, the magnetic declination is 15°E, then the boom orientation from true north is 165°.

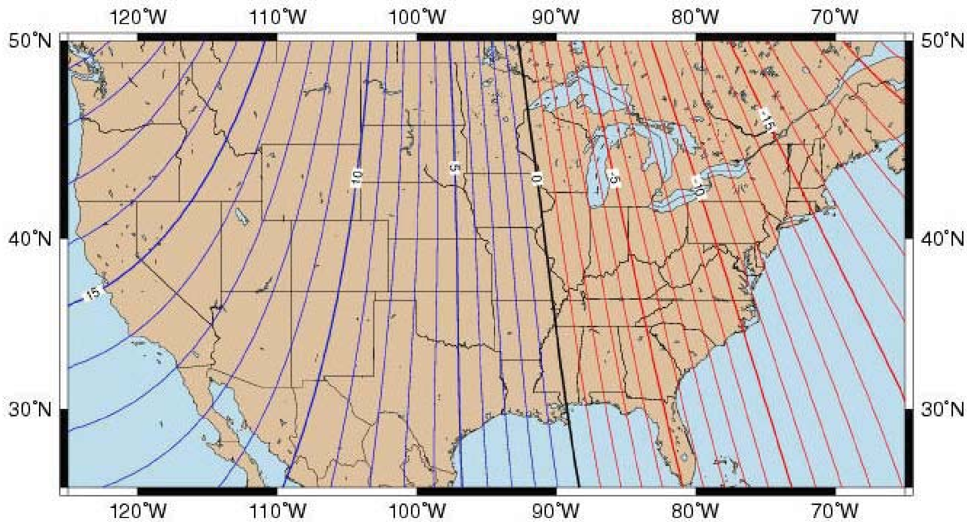


Figure 5-1 Map illustrating magnetic declination for the U.S. in 2004.
(Source: NOAA/National Geophysical Data Center)

5.6. TOWER INSTALLATION

<u>**New Tilt-Up Towers**</u>

Towers can be erected almost anywhere, but the task is much easier if the terrain is relatively flat and free of trees. If the tower is erected on sloping or uneven ground, the guy wires may need to be adjusted often as the tower is raised. If the tower is erected in a wooded or otherwise obstructed area, there must be a clearing around the tower large enough for the tower to lie flat and the guy wires to be anchored. The required clearing for guyed tilt-up towers can be large. For example, a 60 m tilt-up tower is guyed in four directions from the tower's base. The outermost guy anchor at each corner is 50 m (164 ft) from the base. Thus, the four anchor points form a square roughly 71 m (233 ft) on a side. When the tower is lying flat, it extends about 10 meters (33 ft) – plus the length of any lightning mast or vertical sensor boom – beyond one of the outermost anchors. This creates a kite-shaped footprint, with two sides of 71 m and two sides of at least 80 m. (See Figure 5-2)

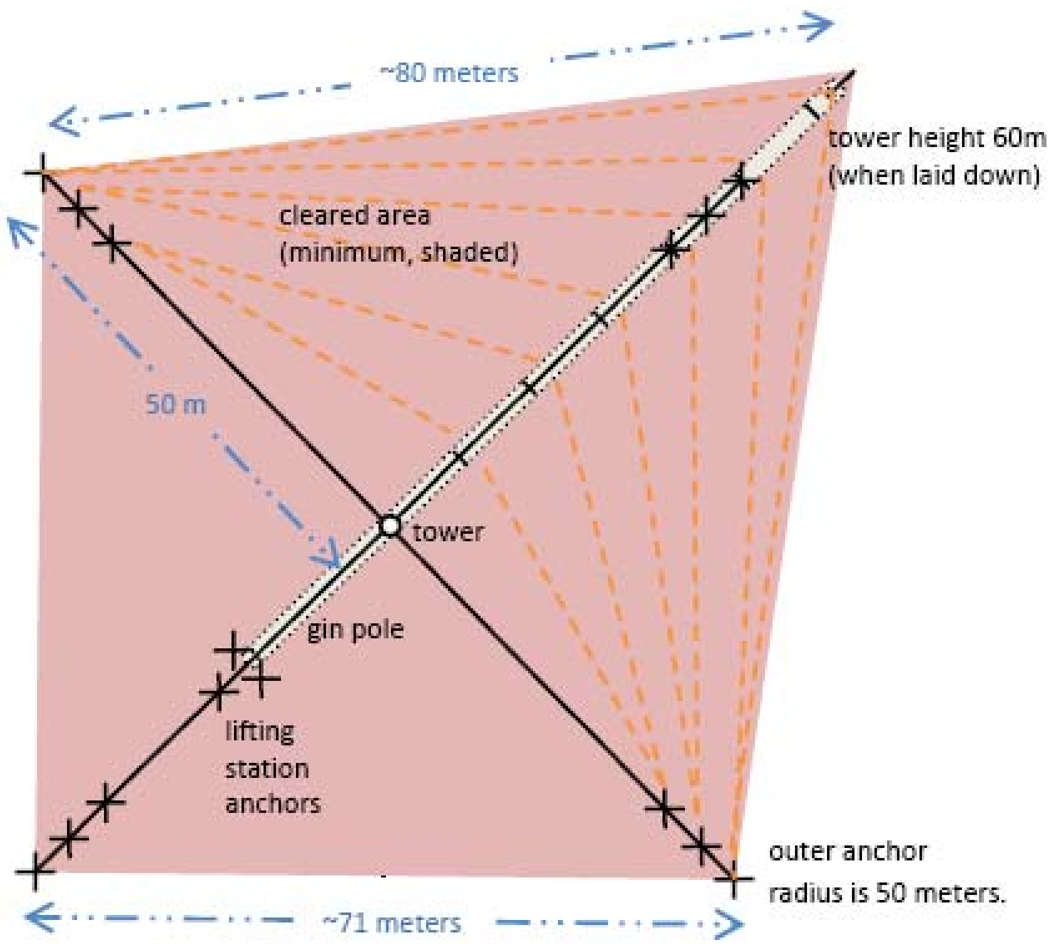


Figure 5-2 The diagram illustrates the footprint of a tilt-up tower. In this example, the prevailing wind direction is assumed to be from the southwest. The "X" marks indicate anchor points. The orange dashes represent the guy wires as the tower is being raised, and the black lines indicate the path of the guy wires when the tower is fully erected. (Source: AWS Truepower)

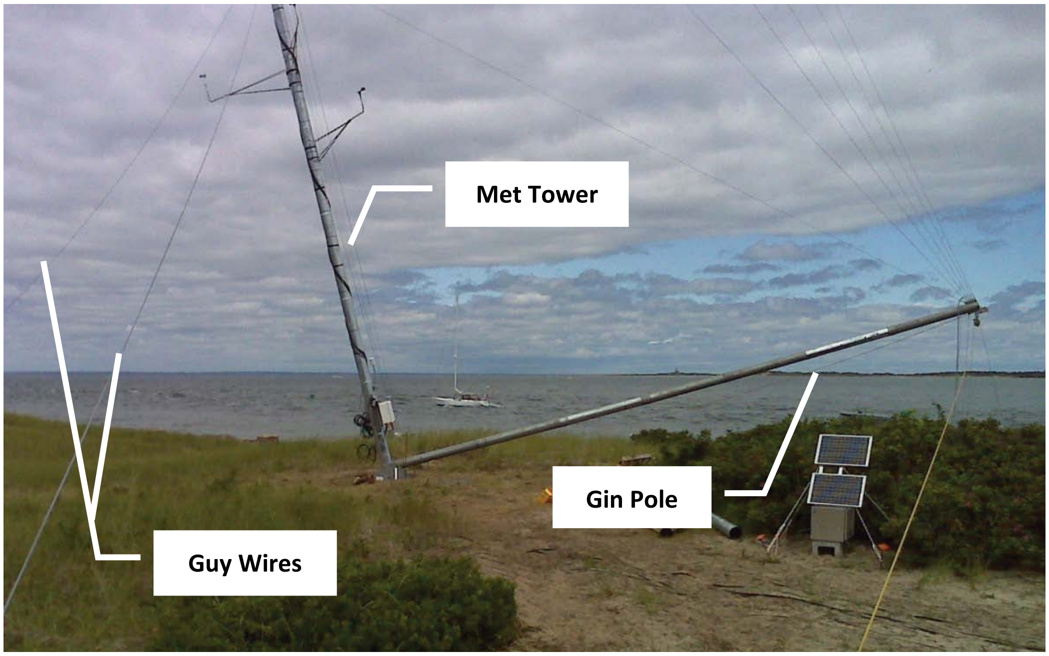


Figure 5-3 Tilt-up meteorological tower being raised with a gin pole. (Source: AWS Truepower)

It is recommended that the guy anchors be located at four of the eight primary directions (N, NE, E, SE, S, SW, W, NW) with respect to true north, as indicated by bearing reference stakes, and that one of these directions be aligned as closely as possible with the prevailing wind direction. The advantages of this strategy are, first, it is easy to verify the orientations of the sensor booms by taking a bearing from the prone mast, and second, raising the tower into (or lowering it away from) the prevailing wind direction offers a welcome degree of stability by maintaining the lifting guy wires in constant tension. Use caution if the winds are coming from a different direction, as the horizontal loads on the system while being raised or lowered can be high. Additionally, raising or lowering the tower during periods of high winds or gusts is not recommended.

The choice of anchoring system is critical. It depends on the subsurface characteristics at each site, which should have been determined during the initial site investigation. A mismatch between the anchor type and soil conditions could cause the anchor to fail and the tower to collapse. Note that the load-carrying capacity of the soil can vary. For example, saturated soil from a winter thaw may have a much reduced carrying capacity.

If anchors cannot be driven into the soil (because of underground facilities or hazards, for example), then concrete blocks can be used as counterweights. The two main disadvantages of this method are the cost of the anchors and the need to transport them to the site.

Figure 5-4 Example of an screw-in guy anchor installation. (Source: AWS Truepower)

The installation of each guy anchor and lifting/lowering station anchor should adhere to the manufacturer's instructions. The lifting/lowering station anchor, which is normally connected to a winch-and-pulley system, warrants special attention because it must carry the entire tower load. The greatest load occurs when the tower is suspended just above the ground. Since the magnitude of this force is well known, the behavior of the selected anchors in the site soil conditions can be evaluated. If the anchors do not seem sufficient for the soil conditions, alternative anchoring should be identified and implemented prior to tower installation.

Under proper tension, the guy wires keep the tower vertical and minimize sway. Inadequate or uneven tension can cause towers to bend or fall. Refer to the manufacturer's instructions for guy wire tension recommendations. The installation team leader should ensure that all guy wire tension adjustments are made smoothly in a coordinated fashion. It is also advisable to clearly mark the lower guy wires with reflective, high-visibility material (such as brightly colored plastic guy sleeves) to alert pedestrians and vehicle operators. This marking should conform with state and/or local regulations. If animals graze near the site, a fence may be necessary to protect the guy stations and tower.

New Lattice Towers

New lattice towers are usually employed when a tall tower (above 60 m) is required. There are two basic types of lattice towers: guyed and self-supporting. Both versions are usually made of fixed-length sections connected end to end. The sections may be assembled with the tower lying flat on the ground, and then picked up as a unit and put in place with a crane, or they may be stacked in place using a winch and jib pole system.

On a guyed tower, cables are attached at several heights and in at least three directions to stabilize the structure. A self-supporting tower broadens near the base to support the structure above it. Both require a solid base, usually on a concrete foundation. The guyed tower requires anchor stations located approximately 80% of the tower's height from its base. The self-supporting type usually has three legs with a solid footing, such as a concrete pier, under each; typically each side of its footprint is only 10% of the tower's height. Despite their larger footprint, guyed towers are more widely deployed for onsite monitoring than self-supporting towers because they are lighter and consequently less expensive.

In the United States, towers taller than 200 feet (61 m) require FAA marker lights and may also need special paint to increase visibility. The position of the FAA light assemblies should be considered in the monitoring design to minimize interference with anemometers and other sensors. The need to power the lights must also be considered. If grid power is to be used, it must be brought to the base of the tower. Where there is no grid power, FAA lights can be operated by a photovoltaic-battery system. It is recommended that the cost of routing grid power to the tower's base be compared with the cost of investing in a solar system.

Use of Existing Towers

Existing towers such as communications towers can offer several challenges. They come in a range of sizes and lattice designs, with the result that the sensor mounting hardware must often be custom-designed and custom-fabricated. The design needs must be determined during the initial site investigation; this is not a "day-of-installation" task. In addition, it is recommended that each design adhere to the sensor mounting and exposure specifications presented in Section 5.7. For example, to minimize the effect of especially wide lattice towers on speed measurements, much longer mounting booms fabricated from heavier stock may be required. Special attention should be give to the heights where anemometry can be mounted with minimal wind flow disturbance caused by existing equipment already mounted on the tower (e.g., dishes, antennas, and lightning masts).

Unlike tilt-up towers, fixed towers must be climbed for the equipment to be installed, repaired, or replaced. Before climbing is permitted, qualified personnel should evaluate the structural integrity of the tower, especially the climbing pegs, ladder, climbing safety cable, and guy wires (if present). Tower climbers must be properly trained and equipped. Since the work will be performed aloft, the weather must be given close attention. Strong wind can make it difficult to raise mounting hardware. In cold, windy weather, the danger of frostbite may be high, and tasks involving manual dexterity can become very difficult.

Note that adding support booms for anemometers and other instruments can create wind or ice loads exceeding the tower's design specifications. The implications of adding equipment to an existing tower should be reviewed by a qualified engineer.

5.7. SENSOR AND EQUIPMENT INSTALLATION

Sensors should be mounted in a manner that minimizes the influence of the tower, mounting hardware, other equipment, and other sensors. This can be achieved by adhering to the following guidelines, consulting manufacturers' instructions, and referring to the example installation configuration shown in Figure 5-5 and Figure 5-6.

Wind Speed and Direction Sensors

The number of sensor heights depends on the height of the tower. For a 50 m or 60 m tower, three anemometer heights are commonly used, and taller towers may have four; generally vanes are deployed at two heights. The following general guidelines govern the selection of anemometer heights and are applicable to most towers:

- The total number of sensor levels depends on the overall height of the tower. One of the heights should be as close as possible to the expected turbine hub height, consistent with other requirements noted below.
- The heights should be as widely separated as possible to minimize uncertainty in shear, consistent with other requirements noted below. A height ratio of at least 1.6 between the top and bottom anemometers is recommended. For example, if the top monitoring height is 50 m, the lowest monitoring height could be 30 m, since the ratio of the two is 1.66.
- The topmost anemometers, if mounted on horizontal booms, should be at least 10 tower diameters below the top of the tower to avoid effects of flow over the top (known as 3D flow effects).
- The lowest anemometers should be mounted sufficiently high above ground both to avoid undue influence by trees, buildings, and other features, and to measure the wind near the bottom of the turbine rotor plane; around 30 m is typical.
- At projects with multiple monitoring stations (met towers or remote sensing), it is useful to match the monitoring heights between the stations to the greatest extent possible to facilitate comparisons between the stations. For example, it may be useful to have an anemometer mounted low on the tower to compare with measurements from nearby reference towers measuring wind speed at a height of 10 m.

The following two sections illustrate how these guidelines may be implemented for two particular tower types: tubular towers and lattice towers.

Tubular towers

Although generally limited in height to 60 m, tilt-up tubular towers are often used for wind monitoring due to their relatively low cost. The instrument heights on such towers are flexible but usually chosen to minimize the influence of guy wires and guy rings. For example, for the NRG Systems 60 m TallTower, the measurement heights might typically be as follows:

- **57.2 m:** Sufficiently far below the top of the tower to avoid 3D flow effects.
- **47.4 m:** Just above the second highest guy ring. Placing the anemometers above the guy ring assures that the wind speed measurements are not affected by the guy wires.
- **32.0 m:** Just above the guy ring at the joint where the tower diameter changes from 254 mm (10 inches) to 203 mm (8 inches). This ensures the tower diameter is the same as for the anemometers mounted above, which reduces errors in wind shear.

Lattice towers

Lattice towers are usually deployed where towers taller than 60 m are required, and sometimes where severe icing is expected. Lattice tower designs vary widely. In addition to the height, important characteristics to know include the face width, compass orientations of the three or four faces (which determine the possible boom directions), heights of guy rings, the diameter of the lattice tubing (or rod), and for pre-existing towers, the heights and approximate sizes of other instruments already mounted on the tower. Although it is impossible to define suitable anemometer heights for every configuration, typical heights for new, dedicated lattice towers are listed below:

- **80 m:** This height represents the approximate hub height of typical utility scale wind turbines. The tower top should be at least 10 face widths above this height to avoid 3D flow effects.
- **60 m:** This intermediate measurement level is included to provide redundancy and to help define the shear profile. The height chosen should be such that measurements are not affected by guy wires. The effect of guy wires can persist for surprisingly long distances - as far as 40 wire diameters (~0.25 meters for ¼ inch wire) downstream.
- **40 m:** This is approximately the minimum height reached by the blade tip on a large wind turbine.

Sensor Installation Guidelines

Anemometers at different heights should be mounted on horizontal booms pointing in the same direction off the tower. This configuration minimizes possible differences in the influence of the tower on the speed measurements, resulting in a more accurate estimate of wind shear. (This is also the reason the topmost horizontally mounted anemometers should be well below the top of the tower.)

At two or more heights, and usually for the top two heights, the anemometers should be deployed in pairs on separate booms. This redundancy reduces data losses caused by sensor failures and tower shadow. The booms should be level for an accurate horizontal speed reading. They should also be long enough to position the sensor at least 3.75 tower widths from a lattice tower and seven tower diameters from a tubular tower, as measured from the tower face. (For triangular lattice towers, the tower width is the length of one face.) An insufficient boom length can result in significant errors in wind speed measurements caused by the tower's influence on the wind flow.

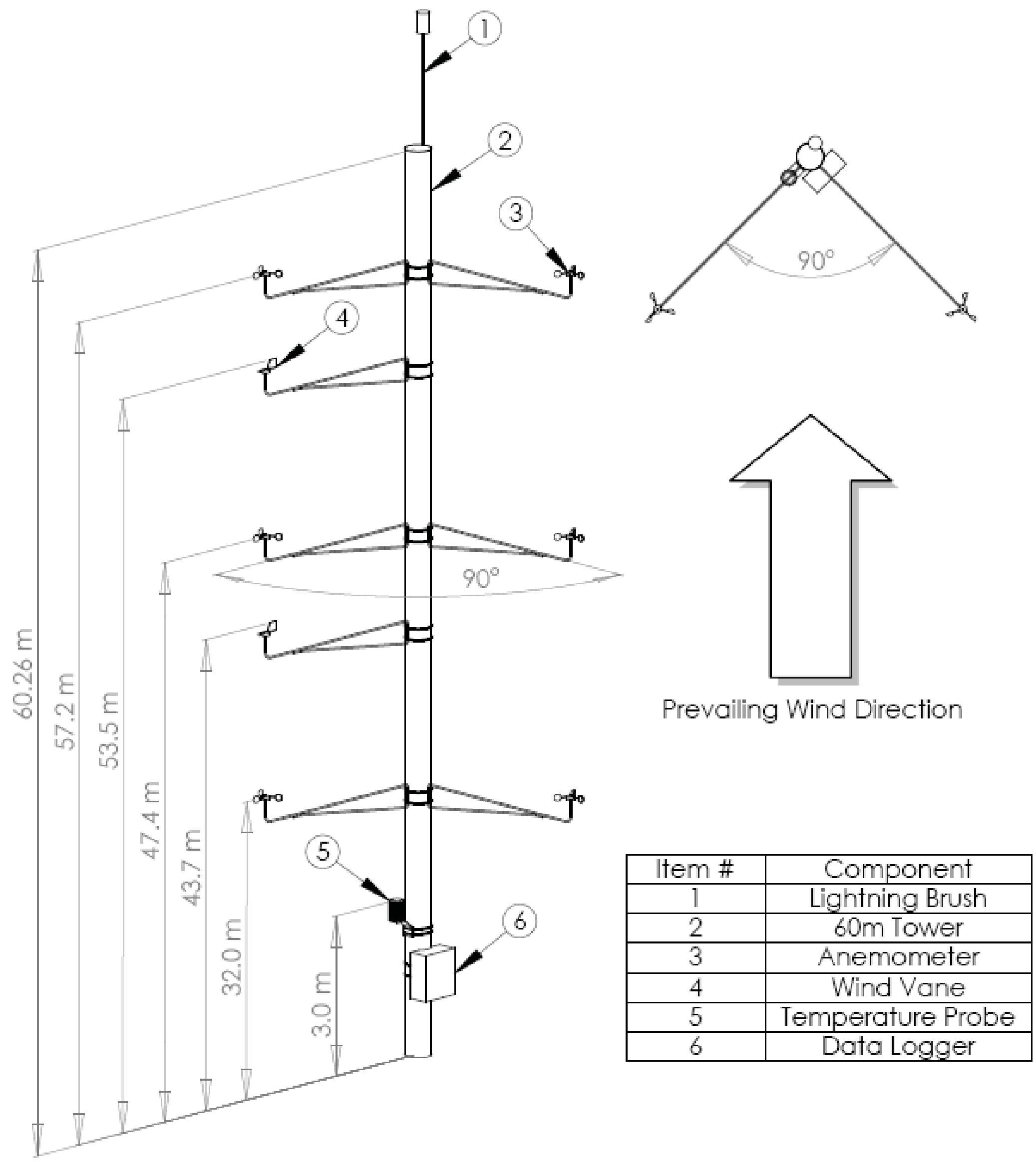
A typical configuration on tubular towers is for the boom pairs to be oriented 90° from one another and 45° on either side of, and facing into, the prevailing wind direction. On triangular lattice towers, the booms are usually mounted on two tower faces 120º apart and 60º on either side of the prevailing direction. It may be advisable to depart from these guidelines, however, if the wind rose shows a strong secondary wind direction. For example, if the wind commonly comes from both the east and west, it may be best to mount the anemometers towards the north and south, 180º apart, if possible. The charts in Figure 5-7, which show typical patterns of wind flow disturbance around tubular and triangular lattice towers, may be used for guidance in boom placement.

Mounting an anemometer on a vertical boom above the tower top is a good configuration for obtaining accurate speed measurements largely unaffected by the tower in all directions. A "goal post" configuration with two such anemometers allows for redundancy. Readings from such vertical top-mounted anemometers should not be combined with readings from lower anemometers to estimate shear, as the effects of the tower on the speed measurements at each height may differ enough to cause a significant error. For this reason, a vertical top-mounted anemometer does not eliminate the need for a pair of horizontal side-mounted anemometers near the top of the tower.

It is customary to install the wind vanes on booms that are at least 1.2 m below the associated anemometer booms. If it is not practical to mount a vane on its own boom, then it should be placed on the anemometer boom about halfway between the anemometer and the tower face. This ensures that the vane disturbs the anemometer readings only when the anemometer is already in tower shadow. Additionally, it is recommended that the vanes be oriented at least 10 degrees away from any guy wires to avoid interference with the vane's rotation as the wires slacken between maintenance visits.

To minimize the influence of the booms on sensor readings, the sensors should be displaced above the booms by a distance equal to at least 12 boom diameters. (For square stock hardware, the diameter equals the length of the vertical side.) Sensor drainage holes must not be blocked by the mounting hardware. Tubing, not solid stock, should be used.

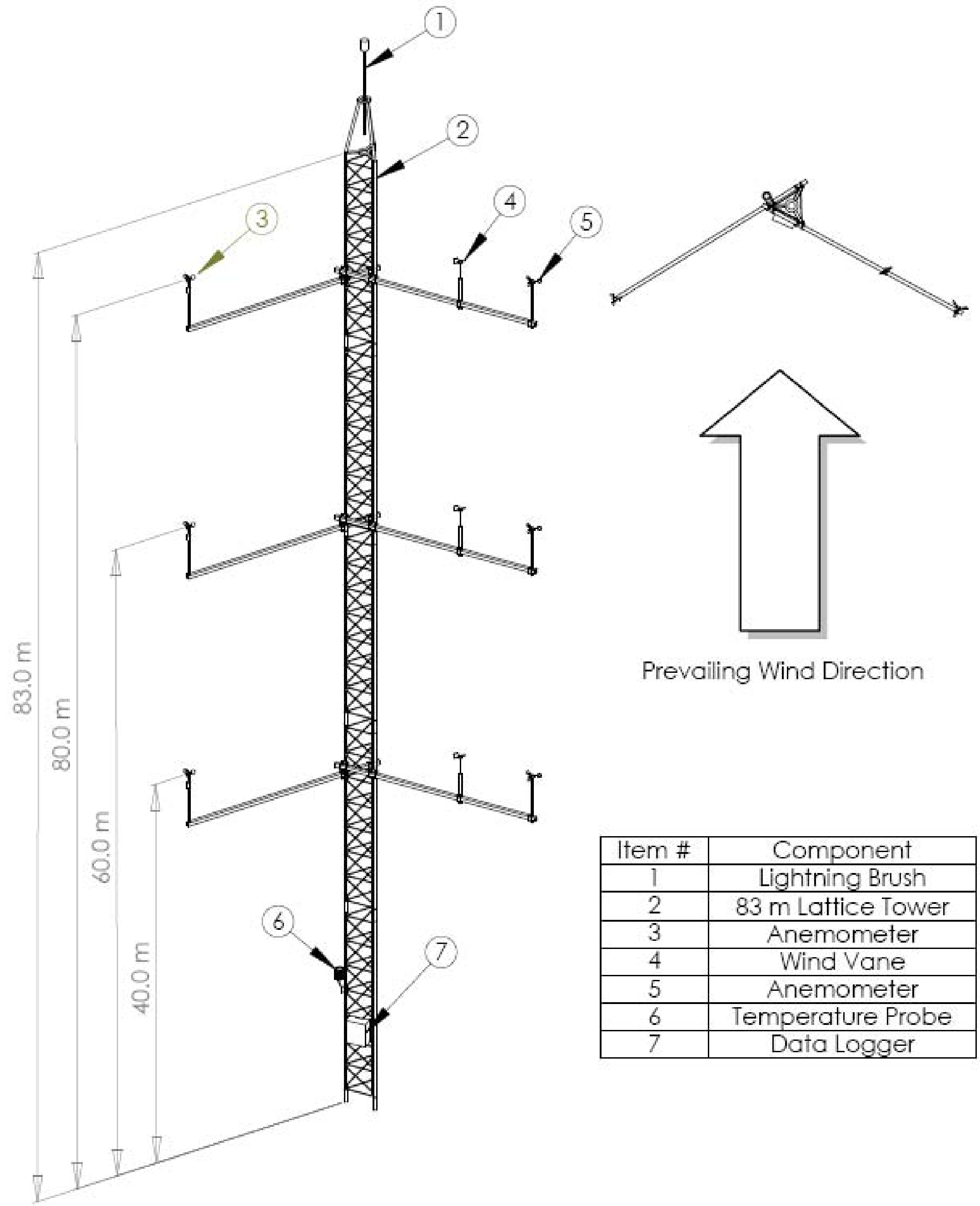
Care must be taken with direction vanes to ensure an accurate direction reading relative to true or magnetic north. Ideally, the wind vane deadband should be oriented along the boom towards the tower. Not only does this ensure that the vane does not spend a great deal of time in the deadband, it allows the deadband orientation to be easily verified from the ground with a sighting compass or sub-meter GPS. The deadband orientation must be documented and entered in the data logger software for the logger to correct and report the wind direction relative to true or magnetic north. Consult the sensor or logger manufacturer's recommendations for determining and reporting the deadband position.



Item #	Component
1	Lightning Brush
2	60m Tower
3	Anemometer
4	Wind Vane
5	Temperature Probe
6	Data Logger

Notes:
- Mount 57.2m anemometer booms just above top guy ring.
- Mount 47.4m anemometer booms just above second highest guy ring.
- Mount 32m anemometer booms 1m above guy ring attower neck down.
- Distances taken from the ground to the sensors (not booms)

Figure 5-5 The above diagram illustrates a typical recommended mounting configuration for a 60 m tubular NRG TallTower. (Source: AWS Truepower)



Item #	Component
1	Lightning Brush
2	83 m Lattice Tower
3	Anemometer
4	Wind Vane
5	Anemometer
6	Temperature Probe
7	Data Logger

Note: Distances taken from the ground to the sensors (not booms)

Figure 5-6 The above diagram illustrates a typical recommended mounting configuration for a 83m guyed lattice meteorological tower. (Source: AWS Truepower)

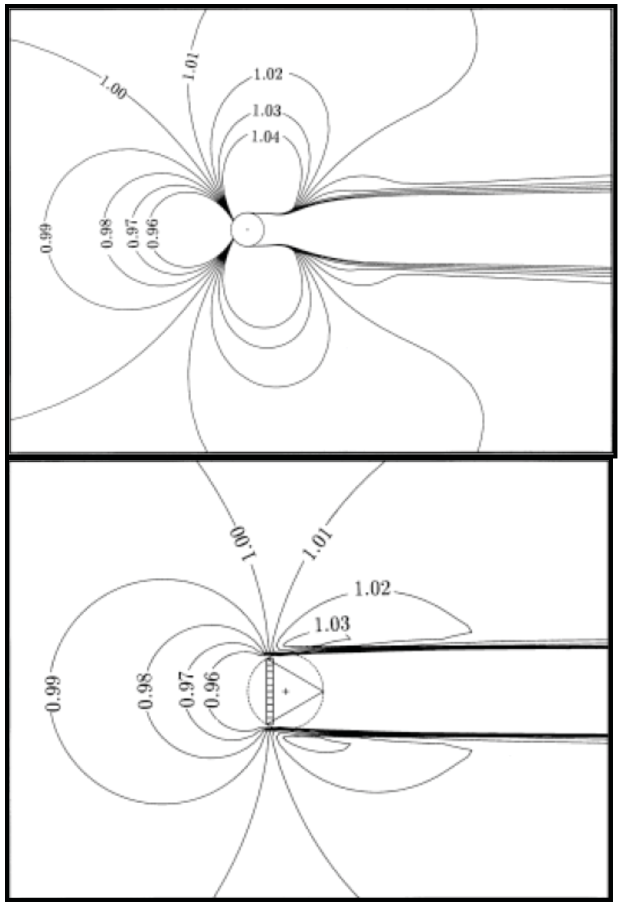


Figure 5-7 The above diagrams illustrate how the airflow is distorted close to the tower; a tubular tower is portrayed on the top, and a lattice tower on the bottom. The wind approaches from the left side of each image. The lines represent contours of constant ratio of the disturbed wind speed to the free-stream wind speed. (Source: IEC 61400-12, Annex G – Mounting of Instruments on the Meteorology Mast.) [9]

Temperature Sensor

A shielded temperature sensor should be mounted on a horizontal boom at least one tower diameter from the tower face to minimize the tower's influence on air temperature. The sensor should be well exposed to the prevailing winds to ensure adequate ventilation at most times. When a set of paired temperature sensors is used for ΔT measurements (see Section 4.2.C), both sensors should be oriented in the same manner (at different heights) to ensure that they are exposed to similar conditions. If possible, mount the sensors on the northern side of the tower to limit heating from direct solar gain; this configuration also reduces the influence of thermal radiation from the tower's surface.

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Data Logger and Associated Hardware

Data loggers should be housed along with their cabling connections, telecommunications equipment, and other sensitive components in a weather-resistant and secure enclosure. One can usually be purchased from the data logger supplier. Desiccant packs (usually provided with the logger) should be placed in the enclosure to absorb moisture, and all openings, such as knock-outs, should be sealed to prevent damage from precipitation, insects, and rodents. It is also important that all cabling that enters the equipment enclosure have drip loops to prevent rainwater from flowing down the cable to terminal strip connections, where moisture can cause corrosion.

The enclosure should be mounted on the tower at a sufficient height above ground to be beyond the likely maximum snow depth for the site. Where applicable, the cellular communication antenna should be attached at an accessible height, usually right above the data logger enclosure. If a solar power system is being used, the solar panel should be placed above the logger enclosure to avoid shading, and should face the south at an angle that will produce sufficient power during the winter, when the sun's apex is low. A near-vertical orientation may be desirable to minimize dust and dirt build-up, which can reduce output.

Sensor Connections and Cabling

The manufacturer's instructions for sensor and data logger wiring configurations should be followed. General guidelines include:

- Exposed sensor terminal connections should be sealed with silicone caulking and protected from direct exposure with rubber or plastic boots.
- Sensor wires along the length of the tower should be wrapped and secured with ultraviolet- and exposure-resistant wire ties or electrical tape. All slack should be removed as the sensor wires are wrapped around the tower. Excessive slack can allow the sensor wires to move in the wind, eventually causing them to break.
- If not installed by the manufacturer, consider installing Metal Oxide Varistors (MOVs) across each anemometer's and wind vane's terminals for added electrical transient protection.
- Where chafing can occur between the sensor wires and supports (such as tilt-up tower anchor collars), the wires should be protected and secured appropriately.

Grounding and Lightning Protection[10]

Grounding equipment is especially important for modern electronic data loggers and sensors, which can easily be damaged by electrical surges caused by electrostatic discharge, lightning, or a difference in ground potential. Most tower and data logger manufacturers provide grounding kits. Nevertheless, different monitoring areas may have different requirements. Sites prone to lightning activity require an especially

[10] For further information regarding grounding, reference the National Electrical Code: Article 250 – Grounding and Bonding.

high level of protection. Additional protective equipment can often be purchased from the data logger manufacturer or supplemented with common materials found at a hardware store. As part of the planning process, the frequency of lightning activity at the site should be investigated. [11] Even with complete protection, it cannot be guaranteed that equipment will survive a direct lightning strike.

Basic Guidelines. The single-point grounding system, presented in Figure 5-8, is the recommended configuration. This setup minimizes the potential for developing an offset voltage by a grounding loop. In this system, the down conductor wire (10 gauge or less) is directly connected to earth ground via a grounding rod, buried ring, or plate (or a combination of these). It should not be routed through the data logger's grounding stud. The sensor drain or shield wires are electrically tied to the same earth ground via the data logger's common grounding buss (terminal strip). Earth ground is an electrical potential (voltage) level referenced to the earth. Typically, the grounding rod, ring and plates are copper-based to provide a low resistivity for charge dissipation.

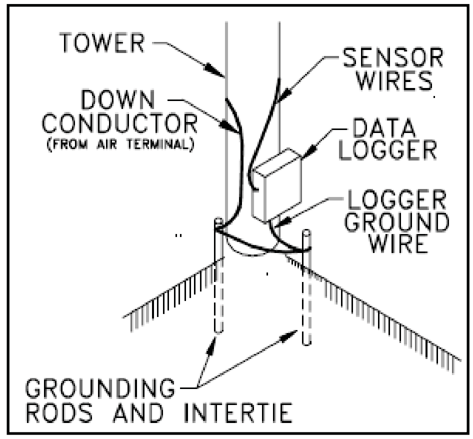


Figure 5-8 Single-point grounding system.

The dimensions of the grounding instrument will determine the contact surface area with the soil, a key element for proper system grounding. A combination of grounding instruments (grounding rod, buried ring or plate) can be used to enhance the contact area if they are all electrically connected. At least one 12.5 cm (½-in) diameter, 2.4 m (8 ft) long grounding rod is needed to provide an adequate soil contact area. A de-oxidation agent should be applied to all mechanical grounding connections to ensure low resistance to ground. The grounding rods should be free of non-conducting coatings, such as paint or enamel, which can interfere with a good soil contact. All grounding rods must be driven below surface. Where rock is encountered, the rod can be driven in at a 45° angle, or buried in a trench at least 0.6 m (2 ft) deep (the deeper the better). Lastly, all grounding rods must be wired together to provide electrical continuity. The above-soil ends of the rods and their electrical conductor attachments should be protected against damage.

It is helpful to know the resistivity of the soil to select the proper grounding system. This is the electrical resistance to current flow within a unit volume of soil, usually located near the earth's surface. It can be approximated by measuring with a multi-meter the resistance between two conductive rods driven into the soil to a specified depth and distance apart. The resistance between the grounding system and the earth should be less than 100 ohms. In general the lower the resistivity of the earth, the better the earth ground it will provide. Soils with low resistivity (e.g., moist dirt) quickly dissipate any voltage potential that

[11] Lightning density maps for the U.S. can be found at: www.lightningsafety.noaa.gov/lightning_map.htm

develops between two points and provide a better earth ground. High resistivity soil (e.g., dry sand) can build up a large potential voltage or current that may be destructive. If the resistivity is high, several grounding rods may be required. Where the soil can freeze, grounding rods should be driven below the frost line.

Soil resistivity often changes seasonally. The value in early spring, following a winter thaw, may not reflect the soil conditions during the midsummer lightning season. In addition, towers in arid climates may be prone to electrostatic discharge if system grounding is poorly done. When in doubt, take the conservative approach and provide added protection. It is, in the long run, the least costly route.

On existing towers, the tower's grounding system should be evaluated. If it is deemed adequate, the data logger's ground may be connected to it. If not, a separate earth grounding system should be installed, and then physically tied into the existing ground system.

Data Logger and Sensor Grounding. Lightning protection devices, such as spark gaps, transorbs, and metal oxide varistors (MOVs), should be incorporated into the data logging system electronics to supplement grounding. Anemometers and wind vanes are available with MOVs as part of their circuitry, or can usually be outfitted with them. Their primary purpose is to limit the peak surge voltage allowed to reach the protected equipment while diverting most of the destructive surge current. The protection offered for each data logger should be verified with the manufacturer. Additional protection equipment may be needed in lightning-prone areas.

Tower Grounding. Lightning protection equipment must be installed on the tower and connected to the common ground. An example of a lightning protection kit consists of an air terminal installed above the tower top, sometimes referred to as a lightning rod, along with a long length of heavy-gauge (10 gauge or less), non-insulated copper wire referred to as the 'down conductor' tied to the earth ground (a grounding rod or buried loop). Due to FAA restrictions, the top of the lightning spike cannot exceed a height of 200 feet above ground unless the tower has appropriate lighting and markings.

Additional Transient Protection Measures. To provide extra protection against electrical transients, a number of additional steps may be taken:

- The sensor wires can be connected to an additional bank of spark gaps (or surge arrestors) before they are connected to the data logger input terminals.
- A longer air terminal rod with multipoint brush head may provide protection for side-mounted sensors near the tower top by placing them within the theoretical 45° "cone of protection". The purpose of the air terminal is to provide a low impedance path for streaming away charged

particles; the cone of protection is the region below the air terminal where lightning flashes are less likely to occur.

- Longer grounding rods may be used. Two benefits are, first, the soil's conducting properties generally improve with increasing depth, and second, additional contact surface area is gained. Rods that fit together to reach greater soil depths are available for purchase.
- High-compression, welds, or copper-clad fittings can be employed for all conductor-rod connections.
- The current carrying capacity of the down conductor can be increased by increasing the cross-sectional area of the wire (i.e., by reducing the wire's gauge).
- The down conductor can be secured to the tower's metal surface with band clamps (one per tower section). Deoxidizing gel helps ensure a good connection.
- A buried copper ground plate or ground ring can be employed at recommended depths to increase soil contact area. It should be connected with other grounding rods.
- Horizontally mounted air terminals can be installed at various levels and directions on the tower to provide additional points for charge dissipation. Each rod should be tied to the down conductor to avoid affecting sensor readings.
- If the tower is secured with concrete or coated (corrosion-resistant) guy anchors, which do not provide a low-resistance path to ground, it is recommended that the guy cables be grounded.

5.8. SITE COMMISSIONING

All equipment should be tested to be sure it is operating before a tilt-up tower is raised or while tower climbing personnel are still aloft. These functional tests should be repeated once the installation is complete. Having spare equipment on hand makes repairs easier if problems are found during these tests.

Recommended tests include the following:

- Ensure that all sensors are reporting reasonable values.
- Verify that all system power sources are operating.
- Verify required data logger programming inputs, including site number, date, time, sensor slope and offset values, and deadband orientations.
- Verify the data retrieval process. For cellular phone systems, perform a successful data download with the home base computer, and compare transmitted values to on-site readings.
- Ensure that the data logger is in the proper long-term power mode.
- Upon leaving the site, the crew should secure the equipment enclosure with a padlock and document the departure time and all other pertinent observations.

5.9. DOCUMENTATION

A complete and detailed record of all site characteristics as well as data logger, sensor, and support hardware information should be maintained in a Site Information Log. An example is provided at the end of this chapter. The following main topics should be included:

- **Site Description:** This should include a unique site designation number, the elevation of the site, the latitude and longitude of the mast and anchors, the installation date, and the commissioning time. The coordinates of the site should be determined at installation using a GPS. Typically, coordinates should be expressed to an accuracy of less than 0.01 minute (about 10 m) in latitude and longitude and 10 m in elevation. The GPS readings should be cross-checked by comparing with coordinates obtained from a topographic map, and any significant discrepancies should be resolved. The GPS datum associated with the measurements should also be recorded so that consistency with the datum used for the turbine layout can be confirmed.
- **Site Equipment List:** For all equipment (data logger, sensors, and support hardware), the manufacturer, model, and serial numbers, the mounting height and directional orientation (including direction of deadbands, cellular antenna, and solar panel), sensor slope and offset values entered in the logger software, and data logger terminal number connections should be recorded.
- **Telecommunication Information:** All pertinent cellular phone or satellite link programming information should be documented.
- **Contact Information:** All relevant landowner and cellular/satellite phone company contact information should be listed.

5.10. COST AND LABOR ESTIMATES

This section describes the main cost elements to be considered when creating a wind monitoring program budget. Also presented is a discussion of staff roles.

The estimated total cost, including equipment and labor, to install a single 50 m or 60 m monitoring station and operate it for two years is roughly US $50,000 to $70,000, not including administrative expenses. For a 80 m lattice tower, the cost range is approximately $170,000 to $190,000. The actual cost will depend on the specific tower type and selected equipment, site access, proximity to operation and maintenance staff, and the number of site visits required.

The monitoring cost can be divided into three main categories: labor, equipment, and other.

- **Labor:** Table 5-1 lists the main tasks to be accounted for when budgeting for labor. Some tasks require just one person, others - especially those that deal with equipment installation and maintenance - require a team of four or five.

- **Equipment:** Equipment costs can be easily obtained from vendors once the measurement specifications are determined. Other items to include in the budget are shipping charges, taxes, insurance, spare parts, and the tools needed to install and service the tower. The estimated total equipment cost for a single site that uses a 60 m tilt-up tubular guyed tower equipped with three levels of sensors is typically $15,000 to $20,000.
- **Expenses:** Related expenses include travel, land lease fees, cellular or satellite phone fee (if applicable), and sensor calibration. Travel costs should account for the anticipated number of field trips required to select, install, maintain, and decommission a site. Some field trips may require overnight lodging and meals. Remote data transfer using a cellular or satellite phone link can add costs, typically $50 to $70 per month, depending on the number and duration of calls and the rates. The re-calibration of anemometers, assuming it is done by the original vendor, is about $300 per anemometer.

Administration
• Program oversight
• Measurement plan development
• Quality assurance plan development
Site Selection
• In-house remote screening
• Field survey & landowner contacts
• Obtain land use agreement & permit
Equipment
• Specify and procure
• Test and prepare for field
• Installation (four to five people)
Operation & Maintenance
• Routine site visits (one person)
• Unscheduled site visits (two people)
• Preventative maintenance activities
• Calibration at end of period
• Site decommissioning (four to five people)
Data Handling & Reporting
• Validation, processing and report generation
• Data and quality assurance reporting

Table 5-1 Labor tasks to account for when budgeting.

Economies of scale can be achieved with multiple towers. Most of the savings are in labor, since staff time and travel can be used more efficiently. Roughly speaking, labor expenses for each additional site should be about 30% less than those for a single site, depending on the number of sites and their proximity to one another. Travel expenses can be reduced if more than one site is visited in a single field trip. Savings on equipment can be realized through vendor discounts and by sharing installation equipment (e.g., gin pole, winch kit) among sites. Overall, the total cost to install and operate a second site is typically about 10% to 15% less than the cost for the first site. The average cost per tower for a five-tower monitoring network is about 20% less than that of a single tower.

A resource assessment program should have a project manager, a field manager, and a data manager, plus additional support staff such as field technicians. Their roles are defined below. Some staff may be able to perform multiple roles.

- The project manager directs the wind monitoring program and ensures that human and material resources are available in a timely manner to meet the program's objectives. The project manager should also oversee the design of and adherence to the measurement and quality assurance plans.
- The field manager is responsible for installing and maintaining the monitoring equipment and transferring the data to the home office. This person, or an assistant, should be available to promptly service a site whenever a problem arises. The installation and decommissioning of tilt-up met towers , as well as service visits that require the tower to be lowered, necessitate a crew of at least five people. For lattice towers, which can be serviced while upright by tower climbers, it is recommended that at least two tower climbers be onsite during maintenance.
- The data manager is responsible for all data-related activities, including data validation and report generation. Familiarity with meteorology and the monitoring site and equipment, and a close working dialogue with the field manager, are essential to properly validate the data.
- The field technicians work closely with the field manager to organize and coordinate many aspects of the resource assessment campaign. The technicians are responsible for evaluating and siting meteorological towers, procuring hardware, overseeing tower installations, conducting verifications of existing towers, and providing maintenance support during campaigns.

SAMPLE SITE INFORMATION LOG

Form Revision Date:

Site Description	
Site Designation	
Location	
Elevation	
Installation/ Commission Date	
Commission Time	
Soil Type	
Surroundings Description	
Prevailing Wind Direction	
Declination	

Site Equipment List						
Equipment Description	Mounting Height	Serial Number	Sensor Slope	Sensor Offset	Logger Terminal Number	Boom Direction (vane deadband)

Telecommunication Information	
Device Manufacturer	
Device Model	
Device SN	
Network ID	
Phone Number	
Programmer	
Date Programmed	
Email Address	
Subject Line	
Password	
Antenna Type	
Antenna Location	
Power Source	

Contact Information	
Landowner Name	
• Address	
• Phone Number	
Cellular/Satellite Company	
• Phone Number	
• Contact Person	
• Contact Extension	

Section 6

6. SITE VISITS

The goal of the operation and maintenance phase is to ensure reliable data collection throughout the wind monitoring program. A host of problems can occur, causing data losses or erroneous readings. Meteorological instruments can be damaged, their mountings can slip, and towers can bend or fall. In addition, various system components from sensors to guy wires may require periodic preventive maintenance.

To address these needs, a simple but thorough operation and maintenance plan that incorporates various quality assurance measures and provides procedural guidelines for all program personnel needs to be developed and implemented. Key elements of the plan include scheduled and unscheduled site visits, inspection procedures, checklists and logs, calibration checks, and spare parts inventory. Guidelines to develop such a program are provided in this section.

Although a sound operation and maintenance plan is critical, ultimately the success of the program depends on the field personnel. They must be thoroughly trained in all aspects of the program, including a working knowledge of all monitoring system equipment. They should be conscientious and detail-oriented. They should also be observant note takers and good problem solvers.

Chapter 6 At-a-Glance

- A simple but thorough operations and maintenance plan should be instituted to preserve the integrity of the monitoring campaign and achieve the desired data recovery target. Two key elements of this plan are the Operation and Maintenance Manual and the Site Visit Checklist.
- The desired frequency of scheduled site visits depends on characteristics of the monitoring campaign such as the data retrieval method (manual or remote), onsite power requirements, and the expected operational life of the instrumentation.
- Ideally, the system operation is monitored remotely through a routine data-screening process. If irregularities are detected, an unscheduled maintenance visit can be carried out.
- The size and scope of a spare parts inventory for a resource assessment campaign should be dictated by factors such as the size of the monitoring network, expected environmental conditions, equipment availability and previous experience.

6.1. SITE VISITS

It is recommended that site visits be conducted according to a regular schedule. The frequency of scheduled visits depends in part on the data recovery method. If the data are retrieved remotely and screened every week or every other week, then the site may have to be visited no more often than once every several months for visual inspection and routine maintenance. Barring any equipment malfunctions, a site visit frequency of once every six months is typically sufficient.

If data retrieval is done manually, however, then site visits should be scheduled according to the capacity of the storage device, and in any event no less often than once every two weeks to ensure that sensor problems are promptly detected through visual inspection or data screening. This strategy should enable the wind monitoring program to attain the recommended target of at least 90% data recovery. The data retrieval process is detailed in Chapter 7.

Situations may arise in which additional, unscheduled visits are warranted. For example, a possible sensor malfunction may be found during routine data screening, or it may be feared that the tower or its equipment was damaged in a storm or under severe icing conditions. To minimize potential data loss, such visits should be carried out as soon as possible after a problem is suspected. Both the program budget and staffing plans should anticipate at least one unscheduled site visit each year.

6.2. OPERATION AND MAINTENANCE PROCEDURES

The operation and maintenance program should be documented in an Operation and Maintenance Manual. The goal of such a document is to provide field personnel with thorough and clear procedures for scheduled and unscheduled operation and maintenance needs. A step-by-step approach, in conjunction with task completion checklists and site visit logs, is a proven and preferred format. The manual should include the following:

Project Description and Operation and Maintenance Philosophy

This section should describe the project and its overall goals. The important role of the technician in maintaining data quality and completeness should be highlighted.

System Component Descriptions

The technician must understand the fundamentals of all system components to ensure proper installation and to perform system checks, and operation and maintenance procedures. A brief description of all instruments (anemometers, wind vanes, temperature probes, data logger, and others) and how they work should be provided. Detailed component information, such as manufacturer’s manuals, should be available for reference.

Routine Instrument Care Instructions

All instruments that require routine maintenance should be identified and maintenance instructions provided. Met tower maintenance activities can be broken down into two categories: structural and instrument maintenance.

Structural

Anchor Condition:

- Check for signs of rust or damage.
- Assess movement of the anchors over time

- Verify the integrity of the anchor connections; for example, the anchor resistance may have changed if an animal has burrowed near the connection point.

Guy Wire Condition:

- Check that the guy wires are properly tensioned in accordance with the manufacturer's guidelines. Tension the guy wires if necessary.
- Inspect the wires and connection points for signs of rust or corrosion.
- Ensure that the appropriate number of wire clips were used to secure the wires, and that the clips are in good condition.

Tower Condition:

- Check for signs of rust or damage.
- Confirm that the tower is plumb and straight.
- For tubular towers, examine the tower for signs of self-flaring at the connection points between tower sections.
- Inspect the baseplate or foundation to ensure that it is not sinking or distorted, and is otherwise free from damage.

Grounding System:

- Verify that the grounding system is connected properly and the electrical contacts are in good condition.

Instruments

Sensors:

- Inspect the booms and stubmasts to evaluate their condition and levelness.
- Confirm that the sensors are at the expected monitoring heights and orientations.
- Replace any sensors that have shown signs of failure through data analysis (see chapter 9).
- Wind vanes and anemometers should be replaced on a regular basis as part of a preventive maintenance plan. A replacement schedule that minimizes discontinuities is recommended (e.g. swap one of each redundant pair of anemometers every year).
- Some anemometer types require periodic refurbishment, such as ball bearing replacement, and recalibration.

Data Acquisition System:

- Inspect the logger and the enclosure for signs of corrosion, damage, moisture, or the presence of rodents/insects.
- Check wiring panel on a regular basis to prevent losing connection to the sensors.

- Check battery voltage and replace batteries as needed.
- Batteries are most often charged by a solar PV system (5 to 50W). The PV system maintenance includes cleaning and realigning solar panels and sensors. The panels and wiring/electrical connections should be checked for cracks and water resistance.
- Refuel and test the diesel generator, if one is used.

Site Visit Procedures

The field visit can be divided into three stages: in-house preparation, on-site procedures, and site departure procedures.

In-House Preparation

- Communicate the reason for the visit and the specific needs to the field staff. Is it a scheduled inspection or is service needed in response to a potential problem? Can the item be addressed with only access to the equipment at the tower's base, or will the tower have to be lowered or climbing be required?
- Where appropriate, notify the landowners of each site to be visited. Maintaining good relationships with landowners can pay off later when negotiating land lease agreements and obtaining permits for the wind project.
- Ensure that field personnel have a complete set of tools, supplies, equipment manuals, and spare parts to accomplish all tasks. The Site Visit Checklist (see Section 6.3) specifies the required tools and supplies. This list should include all equipment necessary to download the site data, such as laptop computers with associated cables and special hardware.
- An extra memory card is a must. Perform an in-house functionality test on each memory card before field installation. This is especially important when swapping memory cards is your primary method of data retrieval. The testing may require a spare in-house data logger to record dummy data onto the memory card.
- Determine the number of people required for the site visit. For safety, tower climbing requires two or more people.
- Have field personnel inform management of where they plan to be and when they expect to return.

On-Site Procedures

- It is recommended that on-site work begin with a "tailgate meeting" in which the day's plans are reviewed. This opportunity can also be used to verify compliance with any Personal Protective Equipment (PPE) requirements and safety procedures.

- If data are to be retrieved during the visit, this should be done first to minimize the risk of data loss from operator error, static discharges, or electrical surges during handling or checking of other system components.
- No matter the purpose, each visit should include a thorough visual inspection (with binoculars or digital camera), as well as testing when applicable, to detect damaged or faulty components. The results should be recorded on the Site Visit Checklist. The inspection should include the following:
    - Data logger
    - Sensors
    - Communication system
    - Grounding system
    - Wiring and connections
    - Power supply (or supplies)
    - Support booms
    - Tower components (for guyed tower systems this includes anchors, guy wire tension, and tower vertical orientation).
- Scheduled component replacements (e.g., batteries), operational checks, and troubleshooting can be conducted at the site. Troubleshooting guidelines should be developed before the first site visit.
- The instantaneous data logger readings should be examined to verify that all measured values are reasonable.
- The Site Visit Checklist should be filled out to ensure that all operation and maintenance tasks have been completed and the necessary information documented.

Site Departure Procedures

- The data retrieval process should be confirmed before leaving a site. This involves completing a successful data transfer with the home-base computer (for remote systems) or in-field laptop computer (for manual systems). For remote systems, data transfer can be verified at the site through the use of a redundant data drop box (such as an e-mail account, FTP folder) that can be accessed from the field. This simple test will ensure the system is operating properly and the remote communication system (antenna direction and phone connections) was not inadvertently altered during the visit.
- Ensure the data logger has been returned to the proper long-term system power mode. Some models have a low-power mode for normal operation to conserve system power. Neglecting to invoke this mode will significantly reduce battery life and may cause data loss.
- Protect your investment. Always secure the data logger enclosure with a good quality padlock. The monitoring stations may attract visitors and invite vandalism.

- Record the departure time and verify that all work performed and observations made have been recorded on the Site Visit Checklist.

6.3. DOCUMENTATION

The Site Visit Checklist, which follows the procedures outlined in the Operation and Maintenance Manual, is a helpful tool for the field technician. It provides a reminder of what needs to be done on each visit and serves as an historical record of the actions taken. A precise, detailed record can help explain any periods of questionable data and may prevent significant data from being discarded during data validation. For these reasons, a standardized checklist should be developed, completed for each site visit, and kept on file.

Example information and activities to detail in the checklist include:

- **General Information:** Site name, technicians, date and time of site visit, and work to be performed.
- **In-House Preparation:** List of necessary tools, equipment and supplies (including spares), documentation, maps, and safety items.
- **On-site Activities:** A sequential list of the various site activities, including equipment checks, data retrieval, tower-related work (raising and lowering procedures), and departure activities.
- **Findings and Recommendations:** A detailed account of the work performed, findings, and observations, and if applicable, further recommended actions.

A sample Site Visit Checklist is provided at the end of this chapter.

6.4. SPARE PARTS INVENTORY

The operation and maintenance plan must anticipate equipment malfunction and breakage. To minimize downtime, an adequate spare parts inventory should be maintained and be available for use during site visits. The basic inventory should consist of all up-tower items necessary to outfit a complete monitoring station, including sensors, booms, and associated mounting hardware. Additional items may be needed. The following points should be considered when determining inventory needs:

- **Size of the Monitoring Network:** The size of the spare parts inventory depends in part on the number of towers in the monitoring network. As a guide, a network with six monitoring towers should have a parts inventory sufficient to outfit two towers. For networks of this size and larger, it is also advisable to have a spare data logger and remote communications device on hand.

- **Environmental Conditions:** Towers in areas prone to extreme weather should have additional spares. Recommended additions include spare anemometers, wind vanes, and sensor mounting booms.

- **Equipment Availability:** The inventory of spares should be increased for items that require an extended lead-time for delivery from the supplier. The turn-around time for critical items, such as data loggers and sensors, is particularly important.

- **Operation and Maintenance History:** Inventories should be adjusted during the program based on experience at each site. Sometimes sensors fail more often than expected, so additional spares may be required.

- **Vandalism:** Certain sites may be prone to vandalism. Cups on anemometers are sometimes used for target practice, and equipment mounted near the ground, such as solar panels or the grounding system, may be stolen. If frequent access is not needed for data retrieval, consider mounting the base equipment (logger and peripherals) higher on the tower, out of easy reach. If vandalism is a concern, consider installing a fence around the base of the tower.

Sample Site Visit Checklist

General Information

Site Designation		
Site Location		
Crew Members		
Date(s)		
Time (LST)	Arrival:	Departure:
Visit Type (check)	Scheduled ☐	Unscheduled ☐
Work Planned		

In-House Preparation

Check each box to denote the items have been acquired.

☐ In-house support person: ________________________________

☐ Copy of Site Information Log.

☐ Acquire necessary tools, equipment, and supplies.

☐ Electrical supplies: voltmeter, fuses, tapes, connectors, cable ties, batteries crimpers, etc.

☐ Wrenches, pliers, screwdrivers, nut drivers, hex set, sledgehammer, wire cutters, etc.

☐ Misc. equipment: silicone, magnetic level, binoculars, camera, GPS, etc.

☐ Spare parts: cabling, anchors, booms and mounting hardware, etc.

1) Sensors:
   1) Sensor: __________ Serial # __________ Slope/Offset: _____/_____
   2) Sensor: __________ Serial # __________ Slope/Offset: _____/_____
   3) Sensor: __________ Serial # __________ Slope/Offset: _____/_____
2) Data logger: Serial # __________

☐ Road and topographic site maps.

☐ Rental equipment: jackhammer w/compressor, truck/trailer, etc.

☐ Winch with 12V battery and battery charger.

☐ Gin pole and associated hardware.

☐ Safety equipment: Hard hats, gloves, appropriate clothes, first aid kit, etc.

☐ Manufacturer's manuals for installation and troubleshooting (sensors, data logger, etc.)

Additional Information/Comments: ____

____

____

____

***Site Designation*: ______________________**

General On-Site Activities

Check the appropriate box. If No, provide and explanation below.

- General Visual Inspection
  Yes ☐ No ☐ Area free of vandalism?
  Yes ☐ No ☐ Tower straight?
  Yes ☐ No ☐ Guy wires taut and properly secured?
  Yes ☐ No ☐ Solar panel clean and properly oriented?
  Yes ☐ No ☐ Wind sensors intact, oriented correctly, and operating?
  Yes ☐ No ☐ Sensors, solar panel, and antenna are free of ice or snow?
  Yes ☐ No ☐ Grounding system intact?
  Yes ☐ No ☐ Cellular antenna correctly orientated?
  Findings/Actions: ____

- **Data Retrieval**
  Manual ☐ Remote ☐ (download method)
  Yes ☐ No ☐ Successful download? If No, provide explanation below.

  Findings/Actions: ____

- **Tower Lowering Activities**
  Yes ☐ No ☐ Check all anchors, no signs of movement?
  Yes ☐ No ☐ Winch secured to anchor and safety line connected to vehicle chassis?
  Yes ☐ No ☐ Gin pole assembled with safety cable and snap links tape?
  Yes ☐ No ☐ Tower base bolt tight?
  Yes ☐ No ☐ Gin pole safety rope attached and tensioned properly (gin pole straight)?
  Yes ☐ No ☐ Weather conditions safe?
  Yes ☐ No ☐ Personnel clear of fall area?
  Yes ☐ No ☐ Note start time of tower lowering. ____________________(LST)
  Yes ☐ No ☐ Winch battery connected and terminals covered?
  Yes ☐ No ☐ Lifting guy wire attachments to gin pole checked?

  Findings/Actions: ____

- **On-Ground General Activities**
  Yes ☐ No ☐ Sensor and ground wires securely attached?
  Yes ☐ No ☐ Grounding system intact and secure?
  Yes ☐ No ☐ Sensor boom clamps secured?

***Site Designation*: ______________________**

General On-Site Activities (continued)

- **On-Ground General Activities (continued)**

  Yes □ No □ Boom orientation OK?
  Yes □ No □ Boom welds OK?
  Yes □ No □ Vane deadband orientation as reported on Site Information Log?
  Yes □ No □ Sensors level and oriented correctly?
  Yes □ No □ Sensor wire connections secure and sealed with silicone?
  Yes □ No □ Signs of sensor damage?
  Yes □ No □ Sensor outputs checked and functioning properly?
  Yes □ No □ Sensor serial numbers as reported on Site information Log?
  Yes □ No □ Sensor and/or data logger replacement? If Yes:

  1) Sensor: __________ Serial #___________ Slope/Offset: _____/_____
     Height: _____ Orientation: _____
  2) Sensor: __________ Serial #___________ Slope/Offset: _____/_____
     Height: _____ Orientation: _____

  Findings/Actions: ____
  ____

- **Tower Raising Activities**

  Yes □ No □ Guy wire collars positioned correctly?
  Yes □ No □ Lifting lines and anchor lines properly attached?
  Yes □ No □ Gin pole secure, lines tensioned, gin pole straight, snap links taped?
  Yes □ No □ Weather conditions safe?
  Yes □ No □ Guys properly tensioned?
  Yes □ No □ Tower straight?

  - Note on-line time: _____________ (LST)

- **Site Departure Activities**

  Yes □ No □ Successful data transfer with office computer?
  Yes □ No □ Checked antenna and phone connections?
  Yes □ No □ Is data logger data/time correct?
  Yes □ No □ Secure data logger enclosure with lock?
  Yes □ No □ Clean area?
  Yes □ No □ Guy wires clearly marked?

Findings/Actions: ____
____

***Site Designation*: _____________________**

Findings and Recommendations

Yes ☐ No ☐ Further actions required? If Yes, describe below:

____

Section

7. DATA COLLECTION AND HANDLING

The main objective of the data collection and handling process is to make the meteorological measurements available for analysis while protecting them from tampering and loss. This chapter highlights the key aspects of meeting this objective, including data storage, retrieval, protection, and documentation.

7.1. RAW DATA STORAGE

Data are typically stored by the data logger in a compact, binary (non-text) file format, which cannot be read without special software. In this form, they are commonly referred to as raw data. To ensure high data recovery during the monitoring program, the data logger's internal storage medium should be non-volatile, meaning its data are retained even if the logger loses power; and the raw data files should be retrieved from the logger before its storage capacity is reached.

Once transferred from the logger to a computer, it is critical that the logger's raw data files be permanently archived and preserved, as they provide the best evidence that the data collected from the mast have not been altered, and they also contain an original record of the conversion constants [12] applied to the raw sensor readings. Without access to these files, an independent reviewer may have doubts about the reliability and accuracy of the measurements.

Chapter 7 At-a-Glance

- Once the met data have been retrieved from the data logger, the raw data files should be securely archived. Access to these files may be requested by independent reviewers.
- Frequent retrieval and review of the raw data are recommended to assure data quality and minimize data loss.
- Modern data loggers have ample storage capacity for most applications, except when the site may be inaccessible for months at a time, or when the desired data sampling interval is much less than 10 minutes.
- It is recommended that detailed records be kept of the data retrievals or transmissions for quality assurance.

<u>Data Storage Types</u>

The following is a list of common raw data storage media.

- **Data Card:** These are small, removable storage devices widely used in digital cameras, camcorders, and similar applications under brand names such as the Sony Memory Stick, MultiMediaCard (MMC), and SecureDigital (SD) card. Many laptops are equipped to read such data cards directly. The data can also be imported into a laptop or desktop computer through a data card reader.

[12] This is of particular importance with data loggers that only provide the converted data rather than the raw outputs of the sensors.

- **Solid State Modules (SSM):** These non-volatile devices, also called internal memory, are hardwired into the logger. The data are read through a direct cable connection from the logging system to a laptop.

- **EEPROM Data Chip**: This is older integrated circuit technology that served as internal memory for earlier loggers. The manufacturer's software and an EEPROM reading device are required for data transfer.

A laptop computer is needed if the data are to be transferred onsite; otherwise the data card can be replaced with a fresh card and brought back to the company office. Depending on the storage type, special cabling, interface hardware, external power supply, and software may be required, along with portable drives or USB drives.

Data Storage Capacity

The minimum required storage capacity of the logger depends on the data retrieval interval (typically once every one or two weeks); the data-averaging interval (typically 10 minutes); the number of sensors being monitored (typically 8-to-12 on a 60 m tower); and the number of parameters calculated and stored by the logger. The capacity of the data storage devices commonly used today – at least 16 MB – is more than ample for most situations. One exception may be when a shorter data-averaging interval, such as two seconds or one minute, is desired. Then larger data storage or more frequent data retrieval may be necessary. Another may be if the tower is likely to be inaccessible for months at a time (because of winter snow and ice, for example). Then, if the telecommunications uplink fails, the logger may be called up to store data for up to several months.

Manufacturers usually provide tables or methods to calculate the approximate available storage capacity (in days) for various memory configurations. Capacity estimates should also allow for delays in retrieving the data.

7.2. DATA RETRIEVAL

The selection of a data transfer and handling process (manual or remote) and the data logger model depend on the requirements of the monitoring program. The following points should be considered:

- Personnel availability
- Travel time to site
- Year-round site accessibility
- Availability of cellular phone service
- Equipment cost

- Types of sensors
- Complexity of initial configuration
- On-site power needs
- Ease of use
- Support systems required (computers, modems, analysis and presentation software, etc.).

7.3. DATA RETRIEVAL FREQUENCY

Frequent data transfer and review are key to achieving high data quality and low losses. A schedule of regular site data transfers, or downloads, should be developed and maintained. The maximum recommended interval for manual retrieval is two weeks. With remote data transfer, the size of the datasets to be transmitted is an important consideration. For reliable transfers, the files should be as small as possible. A weekly schedule may suffice, but a shorter interval, such as every day or every two days, may be better.

Situations may arise that warrant unscheduled transfers. For example, if sensor irregularities are discovered when the data are reviewed, a follow-up transfer may be called for to see if the problem persists. An awareness of icing or severe weather at the site may prompt data retrieval and review to determine if the sensors are still working properly. Of course, whenever problems are suspected, a field crew should be dispatched as soon as possible to inspect the tower and instruments.

7.4. DATA PROTECTION AND STORAGE

The following sections offer guidance to minimize the risk of data loss or corruption.

Data Logger

To ensure data are protected while stored in the data logger, proper installation procedures should be followed, including grounding all equipment and using spark gaps.

Computer Hardware

A personal computer is usually the primary location of the working database, so care should be taken to ensure that the computer and especially its hard drives are in good working order, and that the data are frequently backed up.

Data Handling Procedures

Improper data handling increases the risk of data loss. All personnel in contact with the data and storage media should be fully trained and understand the following:

- Data retrieval software and computer operating system. Technicians should be aware of all instances in which data can be accidentally over-written or erased.
- Good handling practices for all data storage media. Data cards and hard disk drives should be protected from static charge, magnetic fields, and temperature extremes.
- Computer operations and safety practices, including grounding requirements.

To reduce the risk of data loss, the raw logger files should be permanently and safely archived and the working database backed up regularly (at least as often as the data retrieval). Archive and backup copies should be stored in a different location from the main files, not in the same building. Common data backup methods include CD, DVD, and magnetic tape. Online backup services have recently become popular and are especially secure as well as convenient for frequent backups.

With remote data transfers via e-mail, another, very effective data-protection strategy is to set up backup e-mail accounts. The e-mailed files go to different computers in different locations.

7.5. DOCUMENTATION

Additional paperwork is never welcome, but detailed records must be maintained. A Site Data Transmission Report, an example of which is presented at the end of this chapter, should be developed to serve as the master raw data-file log for each site. The report can also be used to track the success of remote data transfers and document file backups. The basic information to include in the Site Data Transmission Report includes:

- Site designation
- Site location
- Data transfer method (manual or remote)
- Last transfer date and transfer time (local and GMT)
- Backup system and location
- Transfer interval
- Comments, problems, actions taken

This documentation provides valuable quality-control feedback on equipment performance and data completeness. For example, a review of past reports may indicate that, although data have been successfully retrieved, establishing and maintaining site communications are becoming increasingly difficult. This may be the first indication of an impending failure of the system's telecommunication or power supply, and suggests it is time to visit the site before data are lost.

Sample Site Data Transmission Report **Date of Report**

Site Number	Site Name	Comments, Problems, Actions Taken	Site Location	Data Transfer Method	Last Transfer Date	Transfer Time		Backup System/ Location	Transfer Interval
						Local	GMT		

Section 8

8. GROUND-BASED REMOTE SENSING DEVICES

As wind turbines become larger and the size and complexity of wind projects increases, there is a need for wind resource data from greater heights and in more locations across a project area. Ground-based remote sensing, which includes sodar (sonic detection and ranging) and lidar (light detection and ranging), can help meet this need. These instruments define the wind profile to heights of 150 m or more above ground, well beyond the reach of tilt-up towers. In settings where fixed masts are prohibitively expensive or not technically feasible, they may be the sole source of wind measurements. More frequently, they are used in conjunction with fixed masts, which remain the standard for resource assessment. While the practice of relying entirely on remotely sensed data is presently rare, it is likely to become more common as the cost of the technology decreases, its accuracy and reliability improve, and experience with it grows.

Chapter 8 At-a-Glance

- Remote sensing with sodars and lidars is generally used for characterizing the wind resource above the height of fixed meteorological masts. This can reduce the uncertainty in energy production estimates. It can also be used to spot-check the resource at multiple locations within a project area.
- Sodars and lidars both measure frequency shifts caused by the motion of the atmosphere. Sodars do this using acoustic pulses, while lidars rely on lasers.
- Not yet widely used as an alternative to fixed meteorological masts, remote sensing is more often employed to complement a conventional monitoring campaign. This is likely to change as its costs decrease and its accuracy and reliability improve.
- Incorporating remote sensing into a wind resource assessment campaign requires considerable expertise in siting, system operations, and data analysis and interpretation.
- Several factors can create discrepancies between measurements made with sodars or lidars and those made with anemometers. Once these factors are accounted for, the mean speeds should replicate anemometer readings within a margin of about 2%.

8.1. INTRODUCTION

The main advantage of remote sensing is the ability to measure wind characteristics above typical monitoring mast heights and across the rotor plane of modern, large wind turbines. This can reduce the uncertainty in wind shear and energy production estimates. Information on turbulence, vertical motions, and directional shear (veer) across the rotor plane - all of which can impact turbine performance - can also be obtained.

Another advantage of remote sensing is that the devices can be deployed and moved relatively easily, so that the wind resource can be sampled at a number of locations within a project area, often at less cost and in less time than with tall towers. In some cases, they can be deployed at sites where it is impractical or prohibited to erect towers. A typical period of measurement, when the systems are paired with long-term meteorological towers, is from a few weeks to a few months, or however long is deemed adequate to obtain a statistically representative sample of atmospheric conditions.

Both sodar and lidar measure the wind very differently from conventional anemometry. The differences between these measurement systems must be considered when comparing wind characteristics derived from them. One difference is that they measure the wind speed within a volume of air rather than at a point. Another is that they record a vector average speed rather than a scalar average speed. Remote sensing units also behave differently from anemometers under precipitation, in turbulence, and where vertical winds are significant; and their performance can be affected by variations in temperature, complex terrain, and other factors.

The next two sections discuss current industry-accepted practices and techniques for integrating ground-based remote sensing into wind resource assessment programs. The first of these sections discusses sodar and its applications. The following section treats commercially available lidar and briefly discusses expected near-term advances. Areas of active methods research and development are identified and discussed. Some providers of remote sensing equipment are listed in Appendix A.

8.2. SODAR (SONIC DETECTION AND RANGING)

Sodar operates by emitting acoustic pulses (audible chirps or beeps) upward into the atmosphere and listening for the backscattered echoes. The scattering is caused by turbulent eddies (small-scale fluctuations in air density) carried along by the wind. The motion of these eddies causes a Doppler frequency shift – the same effect that makes an ambulance siren seem to change pitch as it approaches and then passes an observer. This frequency shift is analyzed by software, which determines the radial wind velocity along the transmitted pulse; the horizontal and vertical wind velocities are derived from the radial velocities according to the geometry of the transmitted pulses. The timing of return echoes establishes the height at which the scattering occurred. Most sodar devices used for wind resource assessment measure the wind profile from 30 m up to about 200 m above ground in increments of 5 m to 20 m. Figure 8-1 illustrates a sodar in operation, and Figure 8-2 shows two particular sodar models.

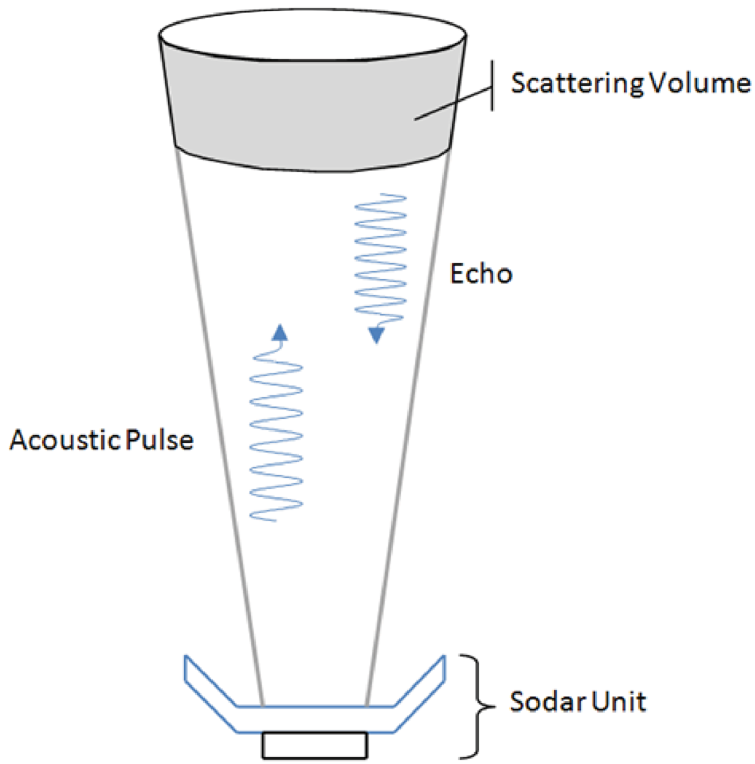


Figure 8-1 Illustration of sodar operation; the sodar unit emits an acoustic pulse and subsequently measures the backscatter from the scattering volume to determine the wind speed. (Source: AWS Truepower)

Figure 8-2 *Left*: Scintec SFAS sodar unit. *Right*: Atmospheric Research & Technology VT-1 sodar unit enclosed within a trailer. (Source: AWS Truepower)

A typical sodar system is equipped with a series of speakers, which function as transmitters and receivers, an on-board computer containing the operating and data processing software (including self diagnostics), a power supply, and a combination data-storage and communications package. Some sodars are trailer-mounted for ease of transport and may be partially enclosed for security and protection from the elements.

The power supply should be sufficient to maintain continuous operation of the sodar and communications equipment. If the sodar is operated off-grid, some means of maintaining battery charge (diesel or gas generator, solar panels, or wind generator) must be supplied. Sodar units (like lidar units) consume more power than most monitoring towers.

Sodar systems can require more complicated data-quality screening and analysis procedures than meteorological masts typically do. There are more parameters to check, differing system responses to atmospheric events (e.g. precipitation), and additional analyses to perform to obtain accurate results. Further analytical effort may also be required in complex flow conditions to obtain readings comparable to anemometer readings. It is consequently recommended that staff carrying out the analysis receive special training or that an experienced consultant be employed to carry out the data validation and preliminary analysis.

Complementary meteorological parameters should be measured at the sodar site to facilitate data-quality screening and improve measurement accuracy. While the ancillary monitoring needs may vary by sodar manufacturer (the configuration of some systems reduces the need for additional monitoring), air temperature and precipitation measurements are key. Air temperature is needed to accurately compute the speed of sound, which in turn determines both the altitude assigned to returned echoes and the vertical tilt of a phased-array sodar's emitted acoustic beams. Precipitation can cause acoustic noise and scattering of sound back to the sodar. It can also invalidate the vertical velocity measurements. For these reasons, periods of measurable precipitation should be carefully scrutinized and likely removed from the sodar data stream.

8.3. LIDAR (LIGHT DETECTION AND RANGING)

Lidar operates by emitting a laser light signal (either as pulses or a continuous wave) which is partially scattered back in the direction of the emitter by suspended aerosol particles. The light scattered from these particles is shifted in frequency, just as the sound frequency is shifted for a sodar system. This frequency shift is used to derive the radial wind speed along the laser path. Multiple laser measurements are taken at prescribed angles to resolve the 3D wind velocity components. The operational characteristics, number of measurement ranges, the depth of the observed layer, and even the shape of the measurement volume vary greatly by lidar model type.

Two distinct types of lidar currently exist for wind resource assessment. *Profiling lidars* measure the wind along one dimension, usually vertically, similar to measurements taken from a tower or sodar. These lidars typically measure wind speeds up to 200 m above the device. *Three-dimensional scanning lidars* have the capacity to direct the laser about two axes, which allows the device to measure wind speed at nearly any angle within a hemispherical volume. This technology is designed to obtain a three-dimensional grid of wind speeds over a large area, with some units having a range of several kilometers. While the scanning lidars have the potential for significant advancement in wind resource assessment, this document will focus on the more extensively tested profiling units.

A typical profiling lidar system is equipped with one or more laser emitters and receivers, an on-board computer containing the operating and data processing software (including self diagnostics), environmental controls (generally, active heating and cooling), and a combination data storage and communications package. While most lidars come equipped to accept AC grid power and have onboard battery back-up in case of a grid outage, a remote power supply must be acquired or custom-built for autonomous operation away from the grid. Like sodar profilers, lidar units can be trailer-mounted for transport and may be partially enclosed for security or environmental protection; most, however, are sold by the manufacturer as stand-alone units. Figure 8-3 depicts two commercially available lidar units.

Figure 8-3 NRG/Leosphere's Windcube lidar (left) and Natural Power's ZephIR lidar unit. (Source: AWS Truepower)

Lidars designed for wind energy applications came on the scene after sodars and are considerably more expensive. Nevertheless, their popularity is growing, particularly in Europe, where most of the leading manufacturers are located. Lidars have benefited from testing campaigns that have helped to establish a reputation for accuracy. In addition, lidars are increasingly being considered for specialized applications, such as offshore wind resource assessment, replacements for nacelle anemometers and deployment within and around existing wind farms for performance measurements. The use of lidar is expected to continue growing in the future as prices decrease and experience with and acceptance of the technology increase.

8.4. REMOTE SENSING CAMPAIGN DESIGN AND SITING

A successful remote sensing campaign, whether it uses sodar or lidar or both, requires considerable expertise in siting, system operations, and data analysis and interpretation.

Both sodar and lidar campaigns should take into consideration the strengths and needs of the overall monitoring program. To help determine the location and duration of the deployment, attention should be paid to existing measurement coverage, seasonal shear variation, likelihood of transient events (e.g., low-level jets, directional shear), and other pertinent parameters. The operational and physical characteristics of the sodar or lidar system may also affect the campaign design.

Similar to meteorological masts, remote sensing systems should be placed at sites that are representative of wind conditions likely to be experienced by wind turbines. The units should be installed level and their orientation relative to true north should be determined and documented.

To prevent noise echoes that may harm data quality, sodars should be placed no closer to obstacles, such as meteorological masts, trees, or buildings, than the height of the obstacles. In many instances, and especially at sites with multiple surrounding obstacles (such as a clearing within a forest), it may be necessary to observe a larger setback. Rotating the sodar so that its acoustic beams are directed away from objects may reduce echoes that cannot be eliminated through setback alone. Nearby active noise sources such as generators, air conditioners, and other emitters of high-pitched tones should be avoided, if possible. Lastly, because the beeping or chirping can disturb people living nearby, the sodar should be sited at least 350 m from homes, and at least 500 m from homes in open, flat terrain.

In theory, because a laser beam is more highly focused than sound waves, lidar is less susceptible than sodar to interference (echoes) from nearby obstacles. This attribute may make it possible to use lidar in locations that would be troublesome for sodar, and to obtain a better match to anemometer data by placing the system closer to the reference meteorological mast. Nevertheless, it is preferable to keep the device's "measurement cone" as unobstructed as possible – particularly from moving objects, e.g. branches, guy wires, and anemometers. While some lidar devices may tolerate the blockage of a significant portion of their field of view, this may reduce data recovery and increase the error margin in the observed wind speed and shear. Other lidar units may accommodate monitoring close to obstacles by rotating the device so that its beams are directed away from them.

The horizontal wind speed derived from both sodar and lidars can be biased in complex terrain. This is because radial measurements are spaced increasingly far apart as the measurement height increases, and in complex terrain the vertical component of the flow may not be homogeneous over the sampling volume. The bias can be as much as 5% in very complex terrain, but is usually much less. This feature of remote sensing measurements, as well as possible corrections for it, is an area of active research. (See section 8.6.)

How much sodar or lidar data must be collected at a site and over what period depends on the wind conditions and the objectives of the study. Where the system is the sole source of wind measurement, at least a year of data collection (12 continuous months) is recommended, just as for monitoring towers. In the more common situation where there is a reference meteorological tower at the site, a much shorter period will usually suffice. Ideally, in this case, the data collected should span a representative range of speeds and directions. This can be accomplished in four to six weeks at most locations. The precision achieved can be estimated by comparing the speeds with simultaneous measurements at a nearby reference mast, or by observing the number of samples in the important direction and speed bins. To further improve confidence in the observed profile, measurements can be taken at different times of year, especially at sites where strong seasonal variations in wind shear are expected.

8.5. DATA COLLECTION AND PROCESSING

Both sodar and lidar systems output multiple parameters. Primary outputs for each monitoring level include horizontal wind speed and direction, vertical wind velocity, and their associated standard deviations. In addition, some indicator of signal quality, such as the signal-to-noise ratio (SNR), as well as the maximum height of reliable data, is usually provided. Understanding the definitions and thresholds for these parameters is useful for establishing appropriate data screening procedures and for identifying suspect data periods.

The recording interval should be compatible with that being used by other measurement systems with which the sodar or lidar readings will be compared (typically 10 minutes). Other averages, such as 60-minute or daily means, can be calculated later, if desired. Clocks in the data recorders of all systems should be synchronized.

Sodar systems record a complete wind profile at each moment of time over a range of heights and at intervals determined by the software settings. The pulse repetition rate (or duty cycle) of the sodar is determined in part by the maximum measurement altitude. Increasing the altitude can reduce the number of valid data samples included in each recording interval. For example, for one common sodar type, setting the maximum altitude to 200 m typically results in about 15% fewer samples per 10-minute recording interval than does setting the maximum altitude to 150 m. Since the SNR is related to sample size, this setting may influence data quality and data recovery, depending on the atmospheric conditions.

The elevations of the lidar range gates can be programmed by the user, but the number of reporting levels is currently limited to between five and 10, depending on the model. Given the limited number of reporting elevations, the reporting heights should be chosen carefully. For example, two of the lidar range gates could be chosen to correspond with the top two tower monitoring levels to enable a direct comparison of absolute speed and shear measurements. A third could be set at the expected hub height, and the remainder spaced across the expected turbine rotor plane.

8.6. COMPARISONS WITH CONVENTIONAL ANEMOMETRY

Since turbine power curves are currently defined with respect to wind speeds measured by cup anemometers, it is important that any sources of bias between sodar/lidar and cup anemometer measurements be understood and eliminated.

Without the adjustments described below, sodar speeds can read 5-7% lower than anemometer speeds. Lidar speeds, too, can differ by up to 4-6% from cup anemometer readings at some sites. When comparing remotely sensed measurements to anemometers, it is equally important to understand, and in some cases correct for, the differing dynamic responses of the individual anemometer models.

The main factors responsible for biases between sodar, lidar, and ordinary anemometers are discussed below. Careful siting, campaign management, and data analysis can effectively treat these issues and may result in remote sensing measurements falling within the uncertainty of high quality anemometer measurements.

Beam Tilt (Sodar)

The tilt angle of the acoustic beam emitted from a phased-array sodar varies slightly with the speed of sound, which is a function of temperature. Such variations can affect the accuracy of the derived speeds. Most sodar manufacturers address this issue by measuring the temperature at the sodar unit and computing the beam geometry in real time. Failure to account for variations in temperature can result in biases of typically 2% to 3% between a sodar and a nearby anemometer.

Vector to Scalar Wind Speed Conversion (Sodar & Lidar)

Sodars and lidars typically compute a vector-average horizontal wind speed at the end of each averaging period. In a turbulent wind field, the varying wind direction causes the vector speed to be less than the scalar speed (the usual output from anemometers) for the same time period. A conversion between the vector and scalar means can be applied if the standard deviation of the wind direction is known (usually from a nearby mast). If it is not known, or if it is desirable for some other reason to use the device's own data to make the conversion, the standard deviation of the vertical wind speed measured by the device can be used to accomplish this. The vector-to-scalar bias correction is typically about 1% to 3%.

Some devices may apply a vector-to-scalar correction during data processing. It is recommended that this be confirmed with the manufacturer.

Environmental Conditions (Lidar)

For all lidar devices, data recovery depends on the background aerosol level. In especially clean air (e.g. high mountain air, and other environments after a rain storm), signal recovery at all monitoring heights is reduced, and measuring speeds at over 150 m height may not be possible. Some lidar devices are also sensitive to backscatter from clouds. While corrective algorithms have been created for these conditions, this is an ongoing area of development. Finally, data collected during periods of precipitation should be scrutinized carefully, and excluded from certain analyses. While the affects of rain and snow on horizontal wind speed measurements may be small, the vertical wind measurements are almost always overwhelmed by the precipitation's downward motion, and should be ignored during these periods.

Turbulence Intensity and Anemometer Overspeeding (Sodar and Lidar)

As noted in Chapter 4, cup anemometers tend to overestimate the mean wind speed in a turbulent wind field because they speed up in a gust more quickly than they slow down after the gust passes. This effect varies significantly by sensor model, and can produce an apparent negative bias in the remotely sensed measurements. Since the dynamic responses of most anemometers have been characterized, methods are available to adjust the anemometer data for overspeeding. This topic is addressed in Chapter 9.

The application of remotely measured turbulence intensity (TI) and its relationship to anemometer-derived TI is an area of active investigation. Nevertheless, the sodar vertical or horizontal TI or the lidar TI may help quantify turbulence-related biases and may potentially be employed for data adjustments. The adjustment is typically on the order of 1-3% of the observed speed, but depends on site conditions and instrument model.

Flow Inclination and Complex Terrain (Sodar and Lidar)

Since sodars and lidars, unlike some cup anemometers, yield a true horizontal wind speed, it is necessary to determine if off-horizontal components due to terrain-following flow are contributing to anemometer bias. In most cases, the necessary adjustment is less than 1%, but in extreme slopes adjustments of up to 3% may be necessary. Since turbines are sensitive to the horizontal wind component, this adjustment should be applied to the anemometer data based upon that sensor's response to inclined flow.

In some cases, particularly over narrow ridgelines and in other complex topography, flow inclination can be non-homogeneous over the sodar or lidar measurement volume. This can induce discrepancies of 3-5% with nearby anemometer readings. The actual effect will vary with the device measurement characteristics (both anemometers and remote sensing units), terrain complexity, land cover and distance between correlated measurements. This topic is an area of ongoing research and investigation. Fully characterizing complex sites and reconciling anemometer and remotely sensed measurements may require bringing additional tools to bear. These tools can include high-resolution flow modeling and high-frequency 3D point and volume measurements.

Volume Averaging (Sodar and Lidar)

Both sodars and lidars measure the wind speed in a volume of air, in contrast to the "point" measurements of anemometers. Each layer measured by sodar (regardless of the height interval at which speeds are reported) actually represents an integral of information in a depth of 20 m or more. In layers where there is high wind shear, the volume averaging will cause the sodar to underestimate the mean speed at the measurement height by up to 3%.

For lidar, the depth of the volume measured can range from less than a meter to more than 50 m. The actual depth depends on the lidar type, and may be either variable or fixed over the entire profile. With greater measurement depth, high shear can introduce a bias similar to that seen in sodar systems.

Distance from Reference Mast

Some types of sodars and lidars must be placed a considerable distance from a reference mast to minimize the mast's interference with the measurements, maximize data recovery, or meet other monitoring needs. In moderate and complex terrain and where there are significant variations in land cover, this can create apparent discrepancies between measurements simply because of the distance between the two locations. Assessing the significance of these discrepancies requires expert judgment, though it may be aided by numerical wind flow modeling.

Once the inherent differences between the measurements systems are accounted for, and assuming a sufficiently short distance to the reference mast considering the terrain, the mean speed recorded by either sodar and lidar should be within about 2% of that measured by a high-quality anemometer at the same height.

PART II

DATA ANALYSIS AND RESOURCE ASSESSMENT

Section 9

9. DATA VALIDATION

After the wind resource measurements are collected and transferred to an office computing environment, the next step is to quality-control (QC) and validate the data. The purpose of this process is to ensure that only valid data are used in subsequent analyses and that the data are as accurate as possible.

While different analysts use different terminology, QC generally refers to the initial screening of data for obvious problems such as logger and sensor failures and data transmission failures. This should be done as soon as possible after the data are transferred from the logger to ensure that instrument problems are discovered as soon as possible.

Data validation, a more involved process, is done less frequently (typically monthly, quarterly, or annually). Validation means, generally, the inspection of data for completeness and reasonableness, and specifically the detection and flagging of bad (invalid or suspect) values in the data record. A number of methods, which are described in detail in this chapter, can be used. It should be noted, however, that no data-validation procedure is likely to catch every bad record, and moreover good data may sometimes be wrongly rejected. Data validation is like any statistical decision process subject to both Type I (false positive) and Type II (false negative) errors. A good data-validation procedure seeks to minimize both types of error.
In this chapter, techniques appropriate for both QC and data validation will be covered under the validation process.

The validation of remotely sensed data is a more specialized topic that is outside the scope of this handbook.

Chapter 9 At-a-Glance

- Before data validation can proceed, the analyst should confirm the monitoring configuration and settings, including anemometer heights, wind vane deadband orientations, anemometer transfer functions, and time stamps.
- Data validation usually proceeds in two phases: an automated screening and a manual review. The automated screening flags potentially suspect data records, while the manual review verifies the results.
- Leading screening criteria include range tests, relational tests, and trend tests. Additional tests are applied to detect tower shadow and icing. The manual review may consider information from a variety of sources to verify data flags.
- Post-validation adjustments can account for tower effects, turbulence, and inclined flow.
- Valid data from anemometers deployed at the same height should be averaged to reduce uncertainty. When one sensor's readings are invalid, the other's should be used.

9.1. DATA CONVERSION

Depending on the data logger manufacturer and model, the data may first need to be converted from the logger's raw binary format to an ASCII text file, a spreadsheet, a database, or some other usable file format. Manufacturers of the most widely used data loggers (e.g., Campbell Scientific, NRG Systems, Second Wind) provide software to do this, which is either part of the logger software or runs on a separate computer.

For accurate data conversion and subsequent analysis, the user must make sure that settings such as the wind vane deadband, anemometer transfer function, and time zone are correctly entered in the conversion software. This may seem like a trivial requirement, but surprisingly many mistakes occur at this stage. For example, it is not uncommon for boom orientations and magnetic declinations to be entered incorrectly in the site documentation, or for anemometer serial numbers to be switched. These and other common mistakes, if not caught at the outset, can lead to significant errors in characterizing the site's wind resource.

For this reason, as a general rule, the analyst should seek independent confirmation of key information whenever possible. For example, photographs may help confirm reported sensor heights and boom lengths and orientations; and scatter plots of the ratios by direction of speeds from paired anemometers can help verify anemometer boom orientations and designations. If no detailed site documentation is available - or if the documentation was provided by another party - a visit to the site to obtain or confirm the required information may be warranted.

Calibrated anemometers should have a certificate provided by the agency that performed the calibration test. The analyst should check this certificate to confirm the sensor transfer function and to verify that the sensor test was normal. There is currently some debate within the wind industry about whether, for calibrated anemometers, the measured transfer function or an average "consensus" function based on numerous tests of different anemometers of the same model should be used when converting raw data. Either method is generally acceptable, although there is evidence that for NRG #40 and Second Wind C3 cup anemometers, in particular, the consensus transfer function yields results that tend to match IEC Class I anemometers employed for power curve testing more closely than the measured functions do. [13]

As a matter of good data-handling practice, both the raw and converted data should be preserved in permanent archives. All subsequent data validation and analyses should be performed on copies of the converted data files. Different file name extensions should be used to avoid confusion. For example, raw data can be given the extension *raw*, while verified data can be given the extension *ver*.

9.2. DATA VALIDATION

In these days of powerful personal computers, most data validation is done with automated tools; however, a manual review is still highly recommended. Validation software may be obtained from some data logger vendors, and commercial software is also available. Firms that do a lot of data validation often create their

[13] Hale, E., "Memorandum: NRG #40 Transfer Function Validation and Recommendation," AWS Truewind, 8 January 2010

own automated methods using spreadsheets or custom software written in languages such as Fortran, Visual Basic, C++, or R.

Whatever method is used, data validation usually proceeds in two phases: automated screening and in-depth review. The automated screening uses a series of algorithms to flag suspect data records. Suspect records contain values that fall outside the normal range based either on prior knowledge or information from other sensors on the same tower. The algorithms commonly include relational tests, range tests, and trend tests.

The second phase, sometimes called verification, involves a case-by-case decision about what to do with the suspect values – retain them as valid, or reject them as invalid. This is where judgment by an experienced person familiar with the monitoring equipment and local meteorology is most helpful. Information that is not part of the automated screening - such as regional weather data - may also be brought into play.

As an example of how this process can unfold, the automated screening might flag a brief series of 10-minute wind speeds as questionable because they are much higher than the speeds immediately before and after. Was this spike real, or was it caused by a glitch in the logger electronics, such as a loose connection? During the review phase, the reviewer might check other sensors on the same mast and observe the same spike; this would suggest it is not a problem with a single sensor or logger channel. Then he or she might look at regional weather records and find that there was thunderstorm activity in the area at the time. The conclusion: the spike was real, and caused by a passing thunderstorm.

In such a two-phase approach, it is reasonable for the automated screening to be somewhat overly sensitive, meaning it produces a greater number of false positives (data flagged as bad although they are actually good) than false negatives (data that are cleared as good but are actually bad). One reason for this bias toward over-detection is that there will be an opportunity to reexamine bad data records in the review phase, whereas good records usually receive no further scrutiny. Another reason is that failing to reject even a small number of bad values can significantly bias a wind resource analysis, whereas excluding a moderate amount of good data rarely has such an impact. Still, care must be taken in designing the automated screening not to overwhelm the review phase with an excessive number of false positives. Finding the right balance takes trial and error.

Validation Routines

Validation routines are designed to screen each measured parameter and flag suspect values for review. They can be grouped into two main categories: general system checks and measured parameter checks.

General System Checks. Two simple tests evaluate the completeness of the collected data:

- **Data Records:** The number of data fields must equal the expected number of measured parameters for each record.
- **Time Sequence:** The time and date stamp of each data record are examined to see if there are any missing or out-of-sequence data.

Measured Parameter Checks. Three measurement parameter checks are commonly performed: range tests, relational tests, and trend tests. These tests are applied in sequence, and data must pass all three to be deemed valid.

- **Range Tests** [14]**:** In range tests, the measured data are compared to allowable upper and lower limiting values. This is the simplest and most common type of test. It presents examples of range-test criteria. A reasonable range for 10-minute average wind speeds is from zero (or the anemometer offset) to 30 m/s. Any values that fall below the anemometer offset should be flagged as either missing or invalid; speeds above 30 m/s are possible but should be verified. The limits of each range test should be set so they span nearly the full range of plausible values for the site. In addition, the limits should be adjusted seasonally, where applicable. For instance, the limits for air temperature and solar radiation should be lower in winter than in summer.

Sample Parameter*	Validation Criteria
Wind Speed: Horizontal	
Average	Offset < Avg. < 30 m/s
Standard Deviation	0 < Std. Dev. < 3 m/s
Maximum Gust	Offset < Max < 35 m/s
Wind Direction	
Average	0° < Avg. < 360°
Standard Deviation	3° < Std. Dev. < 75°
Temperature	Varies seasonally
Typical Range	-35° < Avg. < 35°C
Solar Radiation	Varies seasonally
Typical Range	Offset < Avg. < 1200 W/m^2
Wind Speed: Vertical	Varies with terrain
Average **(S/C)	Offset < Avg. < ± (2/4) m/s
Standard Deviation	Offset < Std. Dev. < ± (1/2) m/s
Maximum Gust	Offset < Max < ± (3/6) m/s
Barometric Pressure	Optional: Sea Level Shown
Average	94 kPa < Avg. < 106 kPa
Differential Temperature	Optional
Average Difference	> 1.0° C (daytime)
Average Difference	< 1.0° C (overnight)
* All monitoring levels except where noted ** (S/C): Simple/Complex Terrain	

Table 9-1 Example range of test criteria.

[14] Note that a variety of voltage measurement systems exist, each intended for different system (communications device, internal battery voltage, external power source measurement). Each system has different operating ranges and care should be exercised when creating range and relational tests for these devices.

- **Relational Tests**[14]**:** These tests rely on relationships between various measured parameters. For example, wind speeds recorded at the same height should be similar (except when one anemometer is in shadow); wind shears between heights should fall within reasonable bounds (which may vary diurnally and seasonally). Table 9-2 gives examples of several relational test criteria. These tests should ensure that physically improbable situations (such as a significantly higher speed at 25 m compared to 40 m) are subject to scrutiny. Comparisons between paired sensors at the same height are especially valuable.

Sample Parameter*	Validation Criteria
Wind Speed	
Max Gust vs. Average	Max Gust ≤ 2.5 * Avg.
60 m / 40 m Average Difference	≤ 3 m/s
60 m / 40 m Daily Max Difference	≤ 5 m/s
60 m / 25 m Average Difference	≤ 5 m/s
60 m / 25 m Daily Max Difference	≤ 8 m/s
Wind Speed: Same Height	
Average Difference	≤ 0.5 m/s
Maximum Difference	≤ 3.0 m/s
Wind Direction	
60 m / 25 m Average Difference	≤ 20°
Wind Shear	Varies with terrain
60 m / 25 m Average	$-0.05 < \alpha^{**} < 0.45$
* All monitoring levels except where noted ** α = wind shear exponent	

Table 9-2 Example relational test criteria.

- **Trend Tests:** These checks are based on the rate of change in a value over time. Table 9-3 lists sample trend test criteria. The thresholds actually used should be adjusted as necessary to suit the site conditions. Note that wind direction trends are not considered because direction can change abruptly during severe weather or frontal passage events, among other conditions.

Sample Parameter*	Validation Criteria
Wind Speed Average	All sensor types
1-Hour Change	< 5.0 m/s
Temperature Average	
1-Hour Change	≤ 5°C
Barometric Pressure Average	Optional
3-Hour Change	≤ 1 kPa
Differential Temperature	Optional
3-Hour Change	Changes sign twice
* All monitoring levels except where noted	

Table 9-3 Example trend test criteria

The examples of validation criteria in Table 9-1, 9-2, and 9-3 are not exhaustive, nor do they necessarily apply to all sites. With experience, the analyst will learn which criteria are most useful in particular conditions.

In addition to these standard tests, two situations usually receive special flags: tower shadow and icing.

- **Tower Shadow:** Tower shadow is identified when two anemometers fail a relational test and the wind is from a direction in which one of them is downwind of the mast. The angular width of the zone of tower shadow depends on the geometry of the mast, but is typically about 30 degrees on either side of a line directly through the tower, i.e., if the boom points due east from the mast, wind directions from 240 degrees to 300 degrees would be flagged. The shadowed region may be different for a lattice tower because the boom is typically offset from the center of the tower. Before applying such a decision rule, it is a good idea to verify the direction of peak shadow and the width of the shaded zone by plotting the ratio of speeds between two anemometers at the same height as a function of wind direction.

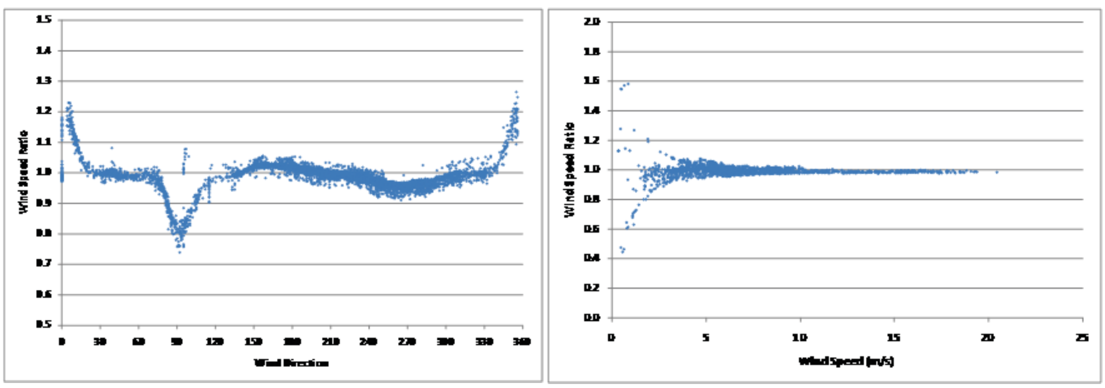


Figure 9-1 – Above are speed ratio plots for a pair of anemometers at the same height as a function of wind direction (left) and wind speed (right). (Source: AWS Truepower)

- **Icing:** Icing events are usually flagged when the standard deviation recorded by the direction vanes is zero or near zero and the temperature is near or below freezing. This is a conservative approach since direction vanes tend to freeze before anemometers do. During periods of detectable icing, it is unwise to rely on anemometer data even if the anemometers indicate speeds above the offset, since they may be slowed by moderate ice accumulation.

Treatment of Suspect Data

After the raw data are subjected to the automated validation checks, a reviewer should decide what to do about the suspect data records. Some suspect values may represent real (albeit unusual) weather occurrences, which should not be excluded from the resource assessment, while others may reflect sensor or logger problems and should be eliminated.

Here are some guidelines for handling suspect data:

- Check to see whether data from different sensors on the same mast confirm the suspect reading. If a transient feature such as a large jump in wind speed is noted at one anemometer, is a similar jump seen at other anemometers? If only one sensor shows the feature, it is more likely that the data for that sensor are invalid.

Code	Rejection Criteria
-990	Unknown Event
-991	Icing or wet snow event
-992	Static voltage discharge
-993	Wind shading from tower
-995	Wind vane deadband
-996	Operator error
-997	Equipment malfunction
-998	Equipment service
-999	Missing data (no value possible)

Table 9-4 Example validation codes.

- Use data from a variety of sources to verify weather conditions. If icing is suspected, is this supported by the observed temperature? If large changes in wind or temperature are seen in the record, do local weather stations indicate a passing weather front that might explain the pattern?
- Examine relationships between sensors over time. Very often, sensor degradation happens so slowly that it goes unnoticed if the data are only examined in periods of, say, two weeks or a month at a time. By examining the relationships over several months or longer, the degradation becomes obvious. Other problems, such as icing, take a limited time to develop and disappear, and moreover may not affect sensors at different heights to the same degree; anemometers sometimes experience slow-down due to ice accumulation before the thresholds signaling an event are crossed. Periods around flagged icing episodes should be scrutinized to be sure the times of onset and conclusion have been accurately identified.
- Assign invalid data a code indicating the suspected reason. Table 9-4 gives some examples. An examination of operation and maintenance logs, site temperature data, and data transmission logs may help determine the appropriate code.
- Maintain a complete record of all data validation actions for each monitoring site in a log file. This document should indicate the main causes of data loss, an explanation for any uncommon events, and whether or not substitution of valid data was possible.

9.3. POST-VALIDATION ADJUSTMENTS

Good sensors mounted correctly should provide accurate measurements of wind speed, direction, and other meteorological parameters most of the time. Nevertheless, there are several factors that often need to be considered to accurately estimate the true free-stream speed. This section addresses three types of adjustments: tower effects, turbulence, and inclined flow. Some adjustments apply only to certain types of anemometers.

Tower Effects

Even outside the zone of direct tower shadow, the presence of the tower can increase or decrease the observed wind speed compared to the true free-stream speed. The effect depends on direction, the sensor's distance from the tower, and the tower width and type. Directly upwind, a tower impedes the wind, reducing the speed; over certain angles on either side of the tower, the tower causes the wind flow to accelerate, producing an increase in the observed speed. (Refer to Figure 5-7.)

Depending on the boom length and tower geometry, these effects can be up to several percent, a significant impact for resource assessment, especially if the wind comes often from a narrow range of directions. For example, it was once quite common to place anemometer booms 180 degrees apart and perpendicular to the prevailing wind direction. This configuration tends to result in an overestimate of the free-stream mean speed at both sensors.

By correcting for these tower influences, a more accurate free-stream speed reading can be obtained for an individual sensor. Currently, however, there are no commercial tools available for doing this, so custom tools must be developed by the resource analyst using information available in the literature. As an alternative, averaging valid data from two sensors at the same height and oriented the recommended angular distance apart (depending on tower type) often mitigates or virtually eliminates tower effects in the combined data record. Data averaging is discussed in more detail in Section 9.4.

Turbulence

Cup anemometers are known to overestimate the wind speed in turbulent flow conditions because of inertia in the rotating cup assembly and because of the tendency of the anemometers to respond more quickly to abrupt increases in speed than to rapid slowdowns. The magnitude of the over-speeding depends on the sensor type and degree of turbulence.

Research has shown that the response of anemometers such as the NRG #40 and Second Wind C3 to turbulence differs from that of IEC Class I anemometers used for turbine power performance testing and certification. The former tend to measure higher speeds than the latter under turbulent conditions. When turbulence is low, the opposite tendency can occur. By correcting the data from the NRG and Second Wind sensors to account for these tendencies, a more accurate energy production estimate can be obtained. [15]

[15] Filippelli, M.V., et al., "Adjustment of Anemometer Readings for Energy Production Estimates," Proceedings of Windpower 2008, June 2008.

In contrast to cup anemometers, prop-vane anemometers tend to underestimate the wind speed under turbulent conditions. This is primarily because the wind direction changes so quickly that the vane cannot keep the propeller aligned perfectly into the wind. Since a propeller anemometer only measures the component of the wind speed that is parallel to the rotation axis, the observed speed is reduced by a factor of the cosine of the angle of deviation. Since greater turbulence produces larger direction shifts, the magnitude of prop-vane under-speeding typically increases with increasing turbulence intensity. [16]

Sonic anemometers, lacking moving parts, are insensitive to turbulence. To bring their measurements in line with those of Class I sensors, however, an adjustment for turbulence may nonetheless be called for, although it is usually small.

Inclined Flow

Wind turbines generate power from the component of the wind that is perpendicular to the turbine rotor. To support an accurate energy production estimate, anemometers should ideally measure only that component. Still, cup anemometers, in particular, are sensitive to varying degrees of off-horizontal winds depending on the geometry of the cups and instrument. Research has documented the impact of flow angle on wind speeds recorded by cup anemometers of various types, [17] but making use of this information requires knowledge of the flow angle at the tower. This can be obtained from a sodar, a lidar, or a vertical anemometer mounted on the mast. Without such a direct measurement, the flow angle can be estimated from the terrain slope and from wind flow modeling. Inclined flow can also occur in flatter terrain for brief periods under low wind and strong surface heating, but this effect is usually small and requires no correction.

9.4. DATA SUBSTITUTION AND AVERAGING

Up to this point, the data validation process has sought to keep valid data from each sensor intact and separate from data from other sensors. In this section two methods of combining the data from different sensors are discussed: substitution and averaging. Data substitution aims to create the longest possible data record by filling gaps in one sensor's record with data from one or more other sensors; data averaging seeks to reduce the uncertainty in the observed speeds by averaging data from two different anemometers at the same height.

Data Substitution

Since a key objective of the wind resource monitoring program is to develop a time series of wind data covering as long a period as possible, it is desirable to fill any gaps in the record with valid data from other

[16] Tangler, J., et al., "Measured and Predicted Rotor Performance for the SERI Advanced Wind Turbine Blades," Proceedings of Windpower 1991, February 1992.

[17] Papadopoulos, K.H., et al., "Effects of Turbulence and Flow Inclination on the Performance of Cup Anemometers in the Field," Boundary-Layer Meteorology Vol. 101, No. 1, 77-107.

sensors, when available. Data substitution is virtually a requirement for anemometers at the top mast height, as well as for the top direction vanes, as they are the most important for assessing the site's wind resource. Whether data substitution is performed for lower-level anemometers or for temperature and pressure sensors is largely a matter of preference. (Note that for reasons discussed in the next chapter, no substituted data should be used for estimating the wind shear.)

For anemometers, the substituted data ideally should come from an instrument at the same height, although in rare instances - such as when both anemometers at the top height have malfunctioned for an extended period - data from an anemometer at a different height may be used. In any case, before the substitution is carried out, a relationship (such as a linear regression forced through the origin, or a simple ratio) between the two anemometers should be established from concurrent, valid data. The analyst should verify that the relationship between them is tight and linear, as otherwise the results may be unreliable. This "field calibration" is especially important when there is a significant, persistent bias between the anemometer readings, which can happen with anemometers of different types (such as heated and unheated) and with anemometers at different heights.

It is generally straightforward to fill gaps in the directional data record using valid data from another vane. The analyst should merely check to make sure that there is no significant, persistent bias between the two vanes' directional readings during periods when both produce valid data. Such a bias could indicate a discrepancy in the boom orientations or vane deadbands, and should be investigated and corrected, if possible. Note that large transient deviations in direction can occasionally arise under light, variable winds; when the wind is strong, however, the directions recorded at heights within 20 to 30 meters of each other, should be nearly equal (within five degrees).

Data Averaging

When anemometers are mounted in pairs at each height on the tower, the question arises; should both sets of measurements be used in characterizing the wind resource, and if so, how should they be combined?

A popular approach is to designate one of each pair of anemometers as the primary sensor and the other as the secondary sensor. The primary anemometer's data are used exclusively for the analysis except when they have been flagged as suspect or invalid. In those periods, the flagged data are replaced by valid data from the secondary sensor in the manner described in the previous section. (If no valid redundant data are available, a gap is left in the data record.)

The underlying assumption of this approach is that the primary sensor is the more accurate of the two. That may be a reasonable assumption in some cases - for example, when the secondary sensor is a heated cup anemometer (heated cup anemometers being generally less accurate than unheated cup anemometers, except, of course, in freezing conditions); when the primary sensor is of superior quality; or when the secondary sensor is in the tower shadow far more often than the primary sensor.

Very often, however, there is no reason to expect either sensor to be more accurate than the other most of the time, so the choice of primary sensor is arbitrary. The preferred method is then to average the data from the two anemometers. Assuming the measurement errors of the two sensors are uncorrelated and of roughly the same magnitude, this method reduces the uncertainty in the observed speed by a factor of the square root of two, or 1.414, compared to relying on the data from one sensor alone.

Averaging can be used only when the data from both sensors are valid; whenever one is shadowed or experiences some other problem, only the other's data should be counted. In those periods the uncertainty reverts back to the uncertainty of the solitary sensor. (Uncertainty in resource assessment is covered in Chapter 14.)

Section 10

10. CHARACTERIZING THE OBSERVED WIND RESOURCE

Once the data validation is complete, the data can be analyzed to produce a variety of wind resource statistics and informative reports. This type of analysis provides a useful summary of the wind resource observed over the course of the monitoring program. Software to do this is available from several vendors, including some data logger manufacturers. Customized reports can also be created with spreadsheet and database software.

Chapter 10 At-a-Glance

- A report summarizing the observed wind resource is normally produced on a monthly, quarterly, or annual basis, as well as at the end of the monitoring program.
- Summary statistics in the report might include the data recovery fraction, observed mean and annualized mean wind speeds, mean wind shear, mean air temperature and air density, turbulence intensity, and wind power density.
- A wind speed frequency distribution chart and fitted Weibull curve help establish how much energy the site might produce at a given mean speed.
- A wind and energy rose indicates the directional distribution of the wind resource, which can strongly influence the turbine layout.

10.1. SUMMARIZING THE OBSERVED WIND RESOURCE

Table 10-1 presents a list of the summary statistics that are most commonly provided in wind resource reports. These statistics, or some subset of them, may be generated on a periodic basis, such as monthly or quarterly, as well as annually and at the end of the monitoring program. A sample monthly report is provided at the end of this chapter (Figure 10-5).

Report Products	Units
Data Recovery Fraction	%
Mean and Annualized Mean Wind Speed	m/s
Mean Wind Power Density	W/m^2
Wind Shear	Non-dimensional exponent
Turbulence Intensity	%
Mean Air Temperature	ºC
Mean Air Density	Kg/m3
Speed Frequency Distribution	Graph
Weibull A and k parameters	m/s (A), non-dimensional (k)
Wind Rose	Graph
Daily and Hourly Speed Distributions	Graph

Table 10-1 Sample Wind Resource Report Statistics

The following sections describe how the various parameters are derived.

Data Recovery

The data recovery (DR) is defined as the number of valid data records as a percentage of the total possible for the reporting period. It should be determined for each wind sensor (for all levels at each site). The method of calculation is as follows:

$$\boldsymbol{DR} = \mathbf{100} \times \frac{\boldsymbol{N_{valid}}}{\boldsymbol{N}}\,(\%) \qquad \textbf{Equation 10-1}$$

where N_{valid} represents the number of valid records and N the total number of possible records in the period. For example, the total possible number of ten-minute records in December is 4,464. If 264 records were deemed invalid, the number of valid data records collected would be 4200 (4,464 - 264). The data recovery rate for this example would be:

$$\boldsymbol{DR} = \mathbf{100} \times \left(\frac{\mathbf{4{,}200}}{\mathbf{4{,}464}}\right) = \mathbf{94.1}\% \qquad \textbf{Equation 10-2}$$

Mean and Annualized Mean Wind Speeds

The mean wind speed is simply the average of the valid speed values for the period in question:

$$\overline{\boldsymbol{v}} = \frac{\mathbf{1}}{\boldsymbol{N_{valid}}}\sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{N_{valid}}} \boldsymbol{v_i} \qquad \textbf{Equation 10-3}$$

The mean wind speed can sometimes be a misleading indicator of the wind resource, however. If the data span a period much shorter than a full year, the mean will not reflect the full seasonal cycle of wind variations. Even if the data span a full year, there may be large gaps in the record that can bias the mean in favor of months with more complete data coverage. And if the data cover more than one year, but not an integer number of years, some months may be represented more often than others, also possibly resulting in biases in the estimated mean speed.

As an example, suppose the data record spans 14 months, with January and February appearing twice. If the winter months are the windiest (as is the case in much of North America), a simple average of the wind speeds for the entire period will probably overestimate the annual average speed, since January and February will be weighted more heavily in the average. Or suppose the period of record spans exactly 12 months, but half the data in the winter months are lost because of icing. In that case, it is likely the calculated mean speed will understate the annual average.

The *annualized mean wind speed* attempts to correct for these problems. Note that this is not the long-term historical mean speed; rather, it is a seasonal correction for the observed period of data. (The long-term adjustment process is explained in Chapter 12.) The annualized mean can be estimated in a variety of ways, but is usually found by calculating, first, the mean for each calendar month in the record, and second, the mean of the monthly means weighted by the number of days in each month. In equation form:

$$\bar{v} = \frac{1}{365.25}\sum_{m=1}^{12} D_m \overline{v_m} = \frac{1}{365.25}\sum_{m=1}^{12} D_m \left(\frac{1}{N_m}\sum_{i=1}^{N_m} v_{im}\right) \quad \textbf{Equation 10-4}$$

The outer sum is over the 12 calendar months, with D_m being the average number of days in month m (28.25 for February, counting leap years). The inner sum is over those speeds that fall within a particular calendar month. The calculation is illustrated in Table 10-2. Here, the data record spans 17 months, from January 2008 to May 2009, with January through May repeated. The straight average of the speeds (taking into account the data recovery in each month) is 7.49 m/s. Still, the annualized average is only 7.39 m/s, because the repeated months are windier, on average, than the other months.

Month	Year	DR (%)	Mean Speed
January	2008	100%	8.94
February	2008	100%	8.35
March	2008	99%	7.63
April	2008	100%	6.79
May	2008	97%	6.56
June	2008	98%	6.58
July	2008	88%	5.81
August	2008	75%	6.25
September	2008	65%	7.50
October	2008	85%	7.85
November	2008	98%	8.26
December	2008	100%	8.36
January	2009	94%	8.68
February	2009	99%	7.37
March	2009	100%	8.13
April	2009	99%	7.00
May	2009	98%	6.85
POR Average		94%	7.49
Annualized Average			7.39

Table 10-2 Sample monthly data record for a station, illustrating the difference between period of record and annualized mean speeds.

Naturally, this method only works if the data record spans at least 12 months; although if it is only one or two months short of 12, an approximate annualized mean can sometimes be obtained by assuming the missing months are similar to the months immediately before and after.

Wind Shear

The wind shear (the rate of change in horizontal wind speed with height) is typically expressed as a dimensionless power-law exponent known as alpha (α). The power law equation relates the wind speeds at two different heights in the following manner:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \qquad \textbf{Equation 10-5}$$

where:

v_2 = the wind speed at height h_2; and

v_1 = the wind speed at height h_1.

This equation can be inverted to define α in terms of the measured speeds and heights:

$$\alpha = \frac{lo \quad \frac{v_2}{v_1})}{lo \quad \frac{z_2}{z_1})} \qquad \textbf{Equation 10-6}$$

Figure 10-1 depicts wind speed profiles for a range of exponents, assuming the same speed at 120 m height.

Time-averaged shear exponents can range from less than 0.10 to more than 0.40, depending on land cover, topography, time of day, and other factors. For short periods, and especially in light, unsteady winds, shear exponents can extend well beyond this range. Typical mean shear values are shown in Table 10-3 for a range of site conditions. All other things being equal, taller vegetation and obstacles lead to higher shear. Complex terrain usually produces higher shear, except on exposed ridges and mountain tops where topographically driven acceleration can reduce shear. Sites in tropical climates tend to have lower shear than similar sites in temperate climates because the atmosphere is less often thermally stable. (The effect of thermal stability is discussed in the next chapter.)

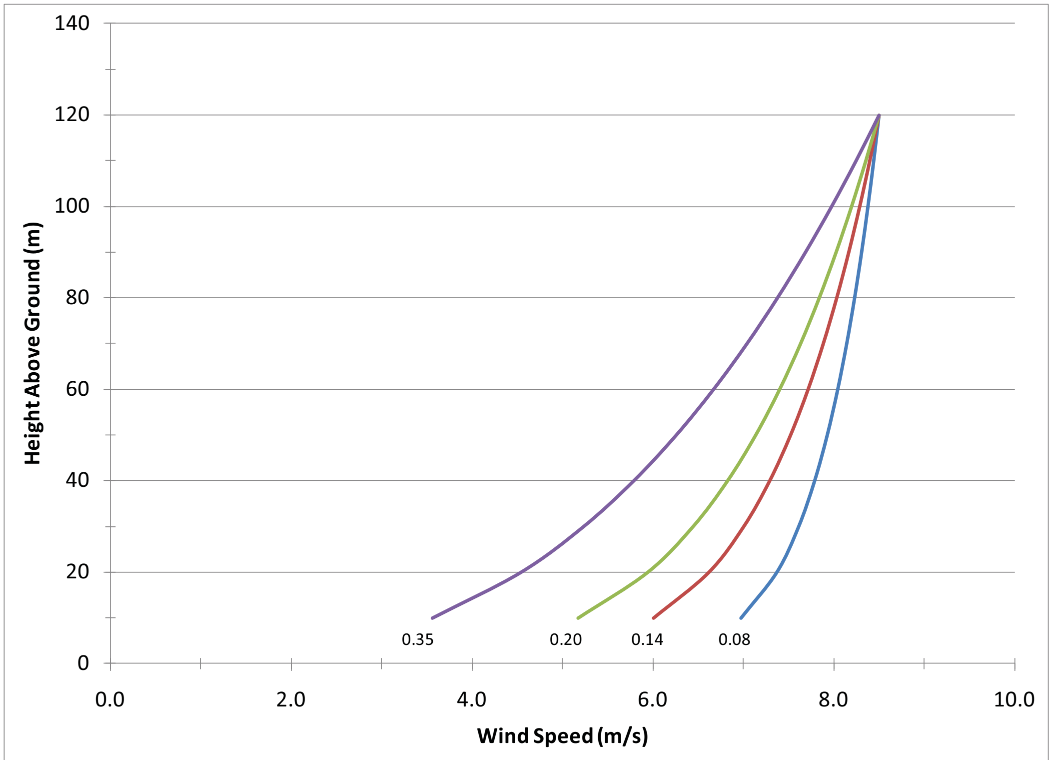


Figure 10-1 Theoretical profiles of wind speed with height for a range of values of the exponent α (0.08, 0.14, 0.20, and 0.35). All curves assume a speed of 8.5 m/s at 120 m height. (Source: AWS Truepower)

Site Conditions (Temperate Climates)	Typical Shear Exponent Range
Open water	0.08 - 0.15
Flat terrain, open land cover	0.16 - 0.22
Complex terrain with mixed or continuous forest	0.25 - 0.40
Exposed ridgetops, open land cover	0.10 - 0.14
Sloping terrain with drainage flows	0.10 - 0.15

Table 10-3 Typical shear exponents for different site conditions. A temperate climate is assumed; shears in warm climates will generally be lower for the same site conditions. These estimates may not be valid for specific sites; measurement is required.

The calculated shear is sensitive to small errors in the relative speed between the two heights, and this sensitivity increases dramatically as the ratio of the two heights, h_1 and h_2, decreases. For anemometers at 40 m and 60 m height (a height ratio of 1.5), for example, an error of 1% in the speed ratio - a reasonable deviation under field conditions - results in an error of 0.025 in the shear exponent. This, in turn, produces an error of 0.7% in the predicted speed at 80 m.[18] For heights of 50 m and 60 m (height ratio 1.2), the same relative speed error produces an error of 0.055 in the exponent and 1.6% in the speed at 80 m. Note that these uncertainties are in addition to the uncertainty of the 60 m measurement alone.

[18] The uncertainty in the shear exponent is given approximately by $\Delta\alpha \cong \frac{\log(1+\varepsilon)}{\log\left({h_2}/{h_1}\right)}$, where ε is the uncertainty in the ratio between the top and bottom anemometers. In a well-designed tower setup with high-quality instruments, ε should be around 1% or less.

Given the sensitivity of the shear to small speed errors, three rules should be followed to produce the most accurate possible shear estimate: (1) The speed ratio should only be calculated using concurrent, valid speed records at both heights. This avoids errors caused by mixing data from different periods or with different rates of data recovery. (2) The two heights in the shear calculation should be separated by a ratio of at least 1.5. This keeps the uncertainty in the calculated shear due to speed and height errors manageable. (3) The speed data should originate from anemometers mounted on horizontal booms with the same directional orientation relative to the tower, so that the effects of the tower on the speed observations will be similar. One implication of this rule is that, in general, data that have been substituted from other sensors should not be used in shear calculations. Instead, only data originally collected from two identically-oriented anemometers are appropriate for this purpose.

Just one average shear value for each pair of heights is usually provided in wind resource reports. This shear is calculated by averaging the concurrent speeds from each anemometer, then taking the ratio and calculating the exponent. (Some analysts choose to exclude speeds below 3 m/s or 4 m/s in this calculation, as shear tends to be more variable in light winds, and low speeds do not contribute significantly to energy production.) In the following chapter, the use of instantaneous or binned shear exponents to extrapolate a time series of wind speed data to hub height, along with possible adjustments to the shear above the top anemometer height, is discussed.

Turbulence Intensity

Wind turbulence, defined as rapid fluctuations in wind speed and direction, can have a significant impact on turbine performance and loading. The most common indicator of turbulence is the standard deviation (σ) of the wind speed calculated from 2-second samples over the 10-minute recording period. Normalizing this value with the mean wind speed gives the turbulence intensity (TI):

$$\boldsymbol{TI = \frac{\sigma}{v}}$$ **Equation 10-7**

where:

σ = the standard deviation of wind speed; and

v = the mean wind speed for the recording interval

The TI generally decreases with increasing wind speed up to about 7-10 m/s, above which it is relatively constant. TI values above 10 m/s typically range from less than 0.10 in relatively flat terrain with few trees or other obstacles, to more than 0.25 in forested, steep terrain. The TI at 15 m/s provides a preliminary indication of the suitability of a turbine model for the project site. The final determination is usually made by the manufacturer, and may take into account the frequency distribution of turbulence as well as turbulence generated by upstream turbines.

Wind Power Density

Wind power density (WPD) is defined as the flux of kinetic energy in the wind per unit cross-sectional area. Combining the site's wind speed distribution with air density, it provides an indication of the wind energy production potential of the site. It is calculated in the following way:

$$\boldsymbol{WPD = \frac{1}{2N}\sum_{i=1}^{N}\rho_i v_i^3\ (W/m^2)} \qquad \textbf{Equation 10-8}$$

where:

N = the number of records in the period;

ρ = the air density (kg/m^3); and

v_i^3 = the cube of the wind speed for record i (m/s)

The air density in this equation must be calculated from other information, as described in the following section.

Note that the cubic equation must be evaluated for each record and then summed, as shown, rather than being applied to the mean wind speed for all records. This is because above-average wind speeds contribute much more to WPD than do below-average speeds, thanks to the exponent. Even then, the WPD estimate is not exact since it ignores variations in speed within each recording interval (whether 10 minutes or 1 hour). The true WPD is thus a few percent greater than that calculated from this formula. This is usually not important for wind resource assessment purposes, since WPD is not used directly in calculating energy production but is an indicator of the overall wind resource of the site.

Air Density

The air density depends on temperature and pressure (thus altitude) and can vary by as much as 10% to 15% seasonally. If the site pressure is measured, the air density can be calculated from the ideal gas law:

$$\boldsymbol{\rho = \frac{P}{RT}(kg/m^3)} \qquad \textbf{Equation 10-9}$$

where:

P = the site air pressure (Pa or N/m^2);

R = the specific gas constant for dry air (287 J/kg·K); and

T = the air temperature in degrees Kelvin (°C+273).

If the site pressure is not available (as is usually the case), the air density can be estimated as a function of the site elevation and temperature, as follows:

$$\boldsymbol{\rho} = \left(\frac{\boldsymbol{P}}{\boldsymbol{RT}}\right)\boldsymbol{e}^{\left(\frac{-}{\boldsymbol{RT}}\right)} \quad (\mathrm{kg/m^3}) \qquad \textbf{Equation 10-10}$$

where:

P_0 = Standard sea-level atmospheric pressure in Pascals (101,325 Pa)

T = Air temperature (K), T(K)= T (°C) + 273.15

g = the gravitational constant (9.807 m/s^2)

z = the elevation of the temperature sensor above mean sea level (m)

After substituting the numerical values for P_0, R, and g, we have:

$$\boldsymbol{\rho} = \left(\frac{\mathbf{353.05}}{\boldsymbol{T}}\right)\boldsymbol{e}^{-\mathbf{0.03417}\frac{}{\boldsymbol{T}}} \quad (\mathrm{kg/m^3}) \qquad \textbf{Equation 10-11}$$

While this equation is quite accurate (to within 0.2% at most sites), the error increases with increasing elevation because the air pressure does not follow the exponential function exactly. For elevations above 2000 m, the following alternative formulation is recommended:

$$\boldsymbol{\rho} = \left(\frac{\boldsymbol{P}}{\boldsymbol{RT}}\right)\boldsymbol{e}^{\left(-\frac{(\mathbf{1.0397}-\mathbf{0.000025}\ )}{\boldsymbol{RT}}\right)} \qquad \textbf{Equation 10-12}$$

<u>Speed Frequency Distribution and Weibull Parameters</u>

The speed frequency distribution is a critical piece of information as it is used directly in estimating the power output of a wind turbine. The frequency distribution represents the number of times in the period of record that the observed speed falls within particular ranges, or bins. The speed bins are typically 0.5 m/s or 1 m/s wide and span at least the range of speeds defined for the turbine power curve, i.e., from 0 m/s to 25 m/s and above. It is usually presented in reports as a bar chart, or histogram, covering all directions. In addition, the speed frequency distribution by direction is stored in a tabular format (by convention called a TAB file), which is used as an input to wind plant design software.

The Weibull distribution is a mathematical function that is often used to represent approximately the wind speed frequency distribution at a site. In the Weibull distribution, the probability density (the probability that the speed will fall in a bin of unit width centered on speed v) is given by the equation:

$$p(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} e^{-\left(\frac{v}{A}\right)^k} \qquad \textbf{Equation 10-13}$$

There are two parameters in the Weibull function: A, the scale parameter related closely to the mean wind speed, and k, the shape parameter, which controls the width of the distribution. Values of k typically range from 1 to 3.5, the higher values indicating a narrower frequency distribution (i.e., a steadier, less variable wind). A commonly observed k range is 1.6 to 2.4. Figure 10-2 illustrates Weibull probability density curves for several values of k and constant A.

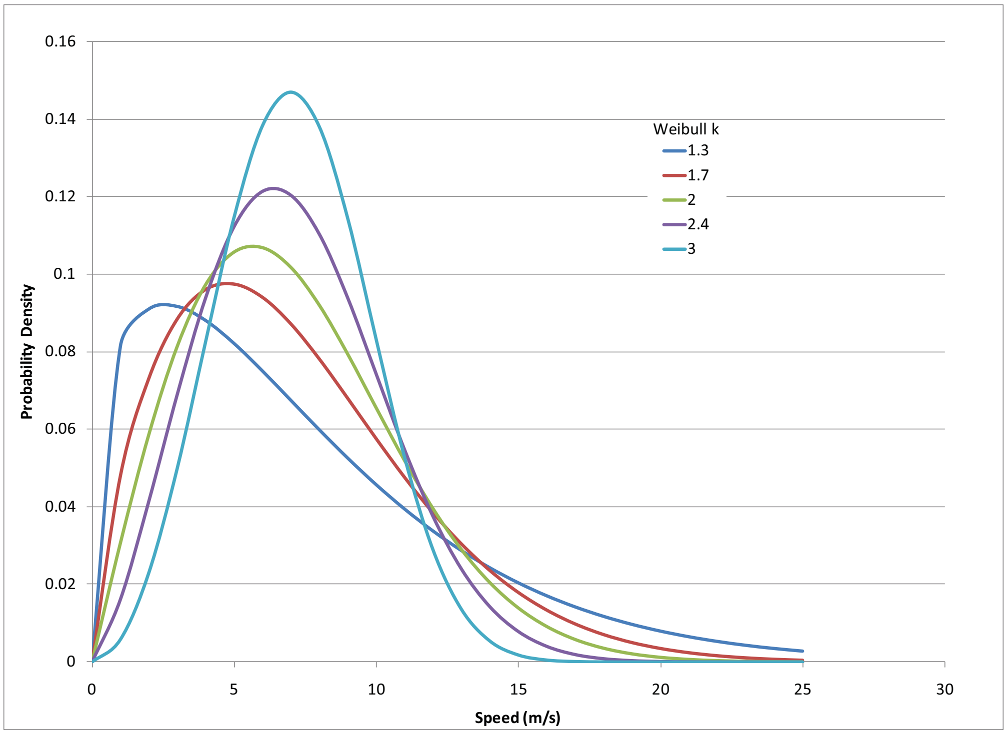


Figure 10-2 Weibull probability density curves for a range of values of k. All curves have the same A: 8.0 m/s. (Source: AWS Truepower)

It is often handy to refer to the Weibull parameters - particularly k - when characterizing a site's wind resource. It is important to keep in mind, however, that the Weibull curve is at best an approximation of the true wind speed frequency distribution. While the real speed distributions at many - perhaps most - sites fit a Weibull curve quite well, there are some sites where the fit is very poor, as suggested in Figure 10-3. For this reason, *the Weibull curve should never be used in place of the observed speed frequency distribution when estimating energy production*, except in a very preliminary way. (Many resource analysts choose to ignore it altogether.)

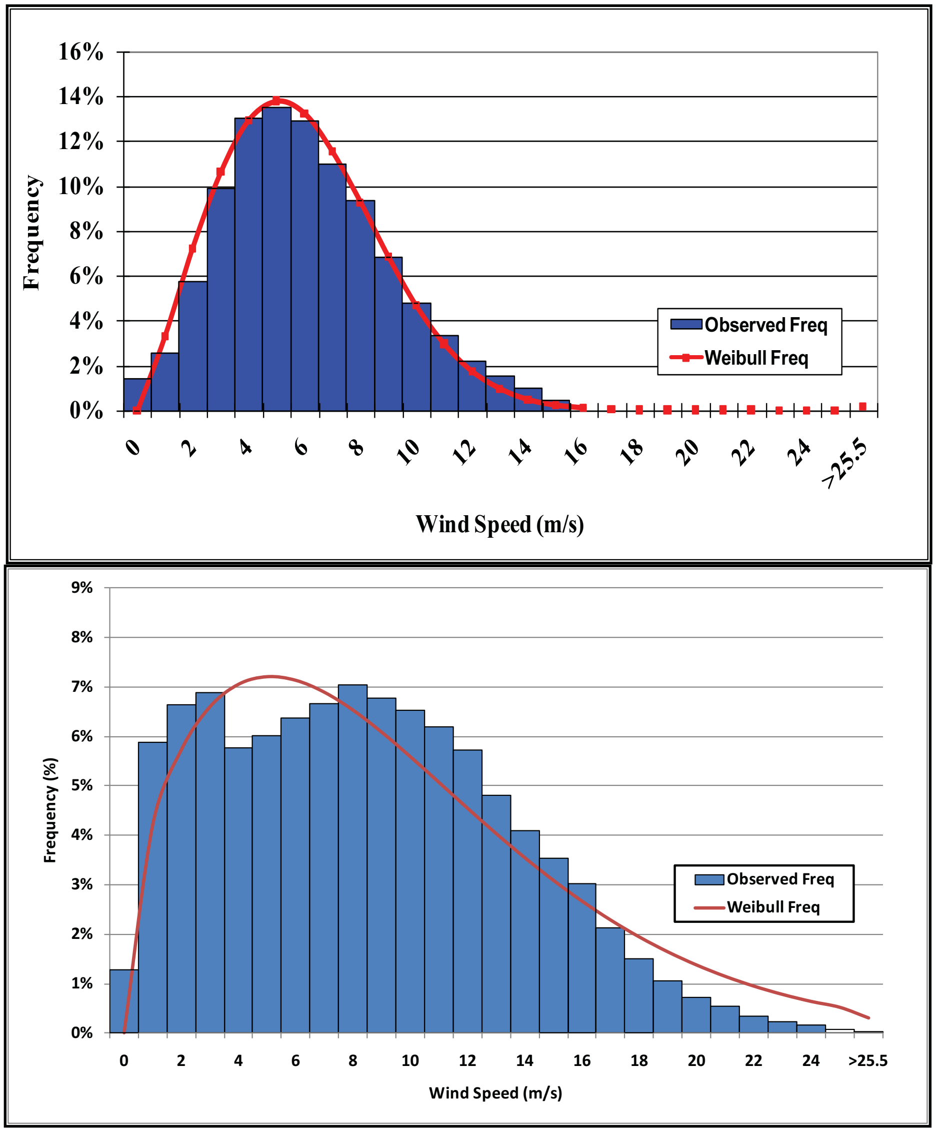


Figure 10-3 Observed speed frequency distributions and fitted Weibull curves. The upper plot illustrates a relatively good fit, the lower plot a relatively poor fit. (Source: AWS Truepower)

There are several analysis software packages that calculate the best-fit Weibull parameters from the observed speed distribution automatically. The process can also be coded quite easily in a spreadsheet or other software. Most analysts prefer an iterative process that produces the same mean speed and wind power density as the observed speed distribution. This can sometimes produce what looks to the eye like a bad fit. That is because such a solution does not generally produce the smallest possible discrepancy between the Weibull and observed frequencies in every speed bin. Since the Weibull parameters are not used directly for the final energy production estimate, the choice of fitting method is a matter of personal preference.

Wind Rose

The directional distribution of the wind resource is a key factor affecting the design of a wind project. In most projects, the spacing between turbines along the principle wind direction is much greater than the spacing perpendicular to it. This configuration maximizes the density of wind turbines while keeping wake interference between the turbines, and hence energy losses, manageable.

A polar plot displaying the frequency of occurrence, mean wind speed, or percentage of total energy as a function of direction is called a wind rose. The wind rose plot is created by sorting the wind data into the desired number of sectors, typically either 12 or 16, and calculating the relevant statistics for each sector:

Frequency: $f_i = 100\frac{N_i}{N}(\%)$

Mean speed: $\overline{v_i} = \frac{1}{N_i}\sum_{j=1}^{N_i} v_j \left(\frac{m}{s}\right)$

Percent of total energy: $E_i = 100\frac{N_i \times WPD_i}{N \times WPD}(\%)$

In these equations, N_i refers to the number of records in direction sector i, N is the total number of records in the data set, v_j is the wind speed for record j, WPD_i is the average wind power density for direction sector i, and WPD is the average wind power density for all records. Figure 10-4 contains a typical wind rose plot, this one showing frequency and percent of energy.

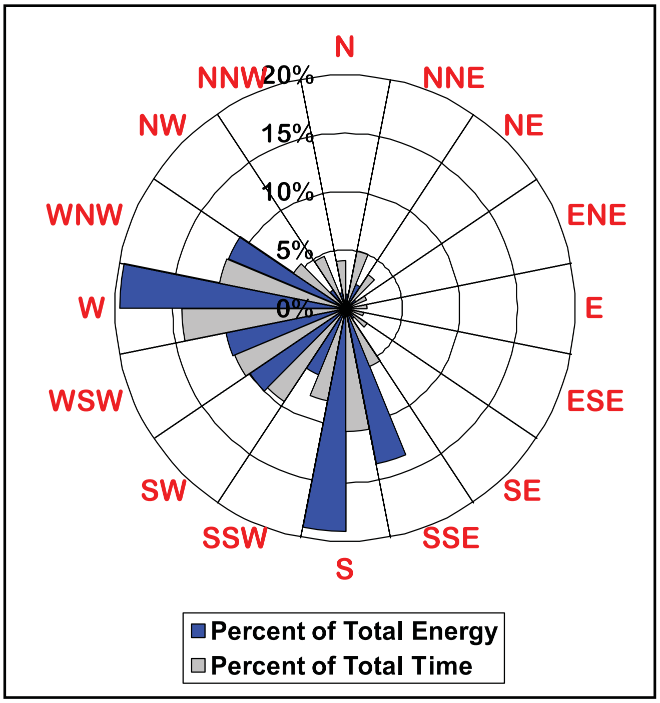


Figure 10-4 Wind rose plot example. (Source: AWS Truepower)

Site Information

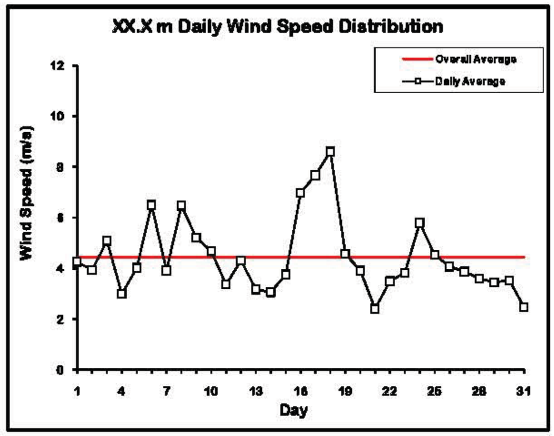
Project: Monthly Assessment of PROJECT for Wind Power Applications
Site: SITE
Location: LOCATION
UTM Site Coordinates: XXXXXX / XXXXXXX (Zone XXX)
Site Elevation: XXX m
Wind Speed Monitoring Heights: XX.X m, XX.X m
Data Averaging Interval: XX minutes
Data Sampling Interval: X seconds

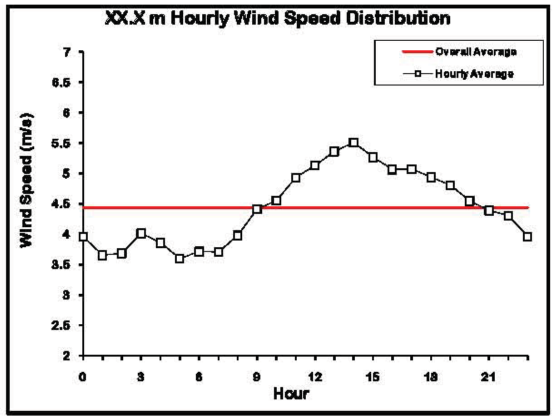
XX.X m Wind Statistics

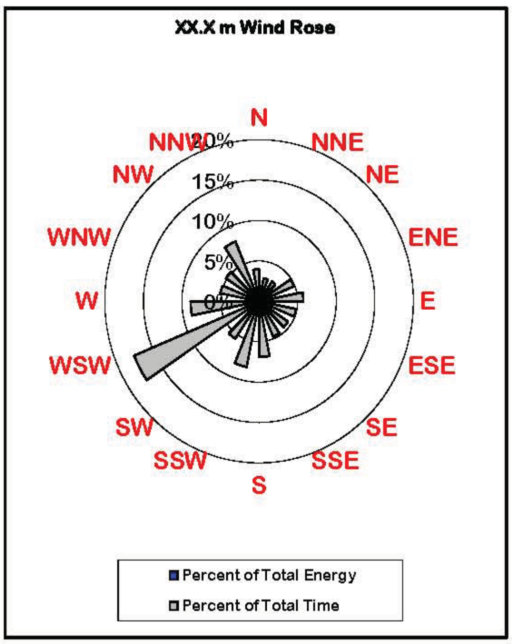
Mean Wind Speed (m/s):	4.43
Average of 10 minute Std. Dev. of Speed (m/s):	0.65
Mean XX / XX m Wind Shear:	0.XX
* Mean Turbulence Intensity:	0.13
Maximum 10 minute wind speed (m/s):	15.0
Prevailing Wind Direction:	XXX
Prevailing Energy Direction:	XXX
Mean Wind Power Density (W/m^2):	XXX
Wind Speed Data Recovery (%):	100

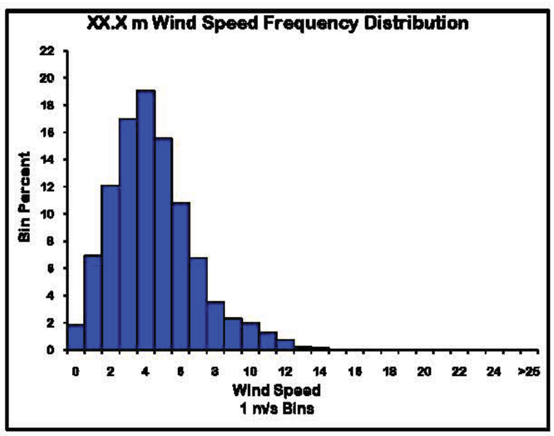
Other Measurements

**80 m Projected Mean Wind Speed (m/s):	X.XX
39.2 m Mean Wind Speed (m/s):	4.13
3 m Temperature (°C):	19.6









*Wind speeds below 4 m/s excluded.
**Projection based on wind speed and shear for current month.

Sensor Status MONTH 2008	
Digital Channels	**Analog Channels**
Ch 1 (XX.X m SPEED - Calibrated): Sensor Operational	CH 7 (XX.X m DIR): Operational
Ch 2 (XX.X m SPEED - Calibrated): Sensor Operational	CH 8 (XX.X m DIR): Operational
Ch 3 (XX.X m SPEED - Calibrated): Sensor Operational	Ch 9 (3 m TEMP): Operational
Ch 4 (XX.X m SPEED - Calibrated): Sensor Operational	Ch 10: No Sensor Installed
Ch 5: No Sensor Installed	Ch 11: No Sensor Installed
Ch 6: No Sensor Installed	Ch 12: No Sensor Installed

Figure 10-5 Sample summary of monthly wind statistics. (Source: AWS Truepower)

CLIENT
SITE
XX.X m Mean Wind Speed (m/s)
MONTH 2009

Day	Hour (LST)																								Daily Avg
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
1	4.0	1.2	0.5	0.8	0.6	1.1	2.5	2.5	3.9	4.9	5.4	6.0	6.0	6.5	6.6	6.9	6.6	7.4	6.8	5.2	5.8	5.1	3.4	2.3	X.X
2	2.6	3.0	3.2	3.8	1.6	2.6	1.9	2.1	2.9	4.1	4.4	5.7	6.5	6.5	7.4	7.3	5.1	4.6	7.6	4.3	2.9	2.2	1.0	1.0	X.X
3	3.3	3.9	5.3	4.4	4.3	3.0	3.9	5.7	5.8	4.8	4.1	4.6	4.6	3.9	6.8	7.5	8.6	8.8	7.6	7.9	4.3	2.5	2.4	4.1	X.X
4	3.0	2.3	0.8	0.9	2.2	3.6	3.6	3.0	2.8	2.7	3.4	4.3	5.1	4.7	3.8	3.0	2.1	2.2	2.1	2.4	3.3	2.2	3.4	4.7	X.X
5	3.4	2.7	4.1	4.7	3.3	3.1	2.0	1.9	2.6	2.8	3.3	3.9	4.3	3.9	4.5	3.7	4.2	2.7	3.3	4.8	5.2	7.5	8.3	6.5	X.X
6	5.6	4.1	3.4	4.7	5.0	4.9	4.5	3.6	4.5	4.7	4.2	6.2	7.5	8.4	9.9	11.6	11.4	10.4	8.8	8.6	7.7	6.3	5.1	5.1	X.X
7	3.5	3.7	2.1	2.6	4.8	4.1	5.0	3.8	1.9	3.1	3.5	2.9	2.9	3.9	5.2	4.7	4.6	5.6	6.0	4.6	4.4	3.1	4.2	3.8	X.X
8	4.5	4.5	4.3	4.9	5.9	5.4	6.6	7.9	8.2	6.0	5.8	6.4	7.0	7.0	8.2	7.8	6.7	7.9	8.1	7.7	6.7	6.1	6.4	5.5	X.X
9	4.9	5.5	5.3	3.5	1.1	1.5	3.4	3.9	4.5	5.8	6.3	5.6	5.6	6.1	6.9	8.6	6.9	7.0	6.8	7.2	3.2	2.9	5.6	6.9	X.X
10	7.7	5.8	4.9	4.4	3.4	5.5	6.2	5.0	6.9	7.6	9.1	7.8	3.2	2.1	1.1	2.0	3.6	3.8	3.4	3.6	4.6	4.4	3.9	2.2	X.X
11	2.5	2.4	1.1	0.5	1.0	2.6	1.7	3.3	2.1	2.2	1.6	4.2	6.1	6.9	6.3	6.2	6.2	5.0	3.8	5.4	4.9	2.0	1.3	1.5	X.X
12	0.6	0.5	2.0	2.7	2.5	1.6	3.4	3.7	3.8	4.3	5.3	5.6	4.9	3.6	4.5	5.7	5.6	7.8	7.6	7.3	6.7	5.5	4.5	3.6	X.X
13	3.2	2.7	3.0	3.4	3.6	3.8	3.3	2.6	3.0	3.8	4.2	3.9	3.9	4.9	7.2	1.9	3.1	2.8	2.2	2.3	1.3	2.5	2.2	1.6	X.X
14	1.6	1.8	1.7	2.2	1.4	0.6	1.4	1.0	1.9	2.8	3.0	2.6	3.7	3.8	4.3	4.9	3.7	5.2	6.1	4.7	2.8	0.8	3.7	7.7	X.X
15	9.2	4.4	4.8	4.4	1.2	1.8	2.0	1.8	1.7	2.7	2.8	3.2	4.3	4.7	4.7	5.3	6.1	6.1	5.0	4.1	3.5	4.0	1.9	0.7	X.X
16	1.6	1.4	0.9	2.8	3.9	3.7	4.2	4.2	4.0	4.0	5.5	6.6	7.7	10.1	10.8	11.3	11.6	12.4	11.9	10.5	9.4	10.7	10.1	8.5	X.X
17	7.1	6.7	6.2	6.3	6.3	5.2	5.1	6.4	7.3	8.9	10.1	9.2	10.9	10.1	9.6	9.7	10.4	9.3	9.3	7.8	6.7	5.3	5.0	5.6	X.X
18	5.3	5.8	5.9	5.7	6.5	6.8	6.7	6.5	8.5	10.0	9.9	11.3	11.6	12.7	13.5	11.2	9.7	9.1	8.5	7.4	8.7	10.3	11.6	3.4	X.X
19	2.9	4.0	5.6	7.7	6.5	6.2	6.4	5.8	6.2	5.1	4.9	3.8	3.8	3.8	3.3	4.8	5.2	4.4	3.5	2.9	3.4	3.6	3.1	3.2	X.X
20	3.6	4.0	4.2	4.2	4.6	4.4	4.3	2.4	2.0	3.1	3.9	4.2	3.6	3.5	4.2	4.1	4.0	3.7	3.7	4.8	4.8	5.0	4.2	3.7	X.X
21	3.5	2.3	2.5	3.1	2.9	2.9	2.4	1.1	1.1	2.0	2.0	2.2	1.8	2.4	1.7	2.3	2.5	0.8	0.9	2.7	4.1	4.1	3.7	2.9	X.X
22	3.5	4.5	6.4	7.3	7.1	3.2	2.3	1.9	2.0	2.6	2.7	2.6	3.0	3.7	4.1	2.6	1.4	0.5	1.7	3.5	4.6	5.2	4.4	3.4	X.X
23	4.0	2.8	2.2	2.5	2.0	4.3	3.9	3.3	3.6	4.9	4.3	3.9	2.9	3.5	3.3	1.9	0.8	2.7	3.9	5.3	5.6	5.9	6.7	7.8	X.X
24	8.9	10.1	9.3	7.6	7.7	6.6	6.2	6.9	6.4	6.9	5.9	7.0	6.2	5.1	4.2	3.2	1.9	2.1	2.7	4.8	6.1	6.4	3.5	3.4	X.X
25	5.3	4.4	4.4	5.1	4.9	5.4	5.1	5.3	6.4	6.3	6.6	5.4	5.7	5.1	4.6	4.6	5.5	4.5	4.0	2.4	2.0	2.5	1.5	1.7	X.X
26	1.7	1.2	0.7	0.7	1.1	0.9	2.2	2.3	3.7	3.9	4.6	5.5	5.4	5.4	5.4	5.6	5.7	6.1	5.2	5.1	6.0	6.4	6.7	6.4	X.X
27	4.9	5.1	3.4	5.4	5.1	4.3	3.8	4.1	3.4	2.9	1.6	2.3	2.4	3.4	3.9	2.5	2.3	3.9	4.2	4.6	5.4	5.0	4.7	4.4	X.X
28	2.8	2.6	4.1	4.8	5.1	2.9	1.9	3.3	4.0	5.7	3.2	6.6	7.0	7.6	3.5	1.9	2.7	2.5	2.0	1.2	1.8	2.0	4.2	3.0	X.X
29	2.5	4.3	5.9	5.7	5.7	5.1	4.8	4.6	5.0	4.7	4.9	3.8	4.1	3.8	2.7	3.0	1.9	1.0	0.4	0.6	1.0	2.2	2.7	2.9	X.X
30	1.9	2.4	2.4	3.5	4.0	2.9	3.5	3.3	2.9	2.4	3.0	3.3	4.1	4.7	4.7	4.4	4.3	3.8	4.7	4.3	3.8	3.3	3.4	3.8	X.X
31	3.9	2.9	3.8	4.4	4.5	1.6	1.3	1.9	0.7	1.5	2.0	2.5	3.5	4.4	4.1	3.5	2.8	3.2	1.5	1.1	0.3	1.3	1.0	1.5	X.X
																									Overall
Hourly Avg	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X	X.X

Figure 10-6 Sample monthly average wind speed summary. (Source: AWS Truepower)

Section 11

11. ESTIMATING THE RESOURCE AT HUB HEIGHT

Since the height of the top anemometers on most towers is below the hub height of most modern, large wind turbines, it is usually necessary to extrapolate the wind resource data to the turbine hub height. This is so not only for wind speeds, but also other information such as air density and turbulence intensity. Here the resource analyst begins to depart from what is strictly measured to what must be assumed or modeled. The task requires a careful and often subjective analysis of information about the site, including the local meteorology, topography, and land cover, as well as the data themselves. This chapter discusses methods of carrying this out.

11.1. MEAN WIND SPEED

The most widely used method of projecting the mean wind speed from the height of observation to the turbine hub height is by means of the power law. This was described briefly in the previous chapter, and the equation is reproduced here:

$$v_2 = v_1\left(\frac{2}{1}\right) \qquad \textbf{Equation 11-1}$$

This time, h_1 and h_2 refer to the top anemometer height and hub height, respectively, and the equation has been rearranged so the known parameters are all on the right. Surprisingly, this equation has no basis in meteorological theory, but it has proved highly useful in practice because it is simple and requires just one parameter, the shear exponent, α. An alternative approach more firmly rooted in theory and used more often outside North America is based on a logarithmic equation. It is discussed later in this chapter.

The key question when applying the power law is what to assume for the shear exponent. It might seem reasonable to use the exponent that was calculated between the first (top) and second heights on the tower; or, if the ratio of those two heights is not large enough to obtain an accurate shear value, between the first and third heights. This is in fact a reasonable starting point; but it is not the end of the analysis.

Chapter 11 At-a-Glance

- The most common method of projecting wind speeds from the top anemometer height to the turbine hub height is through the power law. The main challenge is to determine the appropriate shear exponent.
- The shear measured between different heights on the mast may change with height. Estimating this change requires either direct measurements using remote sensing systems or hub-height towers. Where these are not available, the change must be estimated.
- If the site is in an area of tall, dense vegetation, the wind may be displaced above ground level. This displacement effect results in a decrease in shear with height.
- A single time-averaged shear exponent is not appropriate for scaling a time series of wind speed data or a wind speed frequency distribution, because it does not account for variations in shear. Either instantaneous or binned shear values should be used instead.
- Aside from wind speed, this chapter also addresses how wind direction, air density and turbulence intensity should be projected to hub height.

The challenge is to determine whether the shear exponent changes with height above the mast top. In fairly open and flat terrain, it usually does not change significantly. But this assumption may not hold in other situations, such as where there is dense forest or strong topographic enhancement or blocking of the wind flow, or when the most energetic wind is confined to a relatively shallow layer near the surface, as occurs in thermally driven drainage (katabatic) wind flows. In such situations, adjustments to the mean shear exponent may be warranted.

The following sections discuss several strategies that can be followed to determine what shear adjustment, if any, is warranted.

Direct Measurement

The ideal is to measure the wind shear profile up to and beyond the turbine hub height. This can be done either with a hub-height mast or a ground-based sodar or lidar system. Strictly speaking, such measurements apply only to the locations at which they were taken. Why not then simply measure the profile to hub height at every mast? Desirable though that would be, there are two reasons why it is not usually practical. First, hub-height towers are expensive and difficult to install in some sites. Second, it is often not possible to deploy sodars or lidars right next to an existing mast. This may not matter very much if the site is relatively uniform - open land cover with few trees and little steep terrain - so that the shear is more or less constant across the project area. Then the shear to hub height observed at one location may be applied with some confidence to other locations.

At more complex wind sites, however, the remotely sensed wind profile may not match the profile observed at the site's primary meteorological towers very closely. In that case, one is left to decide how to modify the observed shear at each of the towers to account for the information provided by the hub-height mast or remote sensing systems. One approach is to apply either a ratio or difference shear adjustment:

Difference method: $${}^{(m)}_{h2\to h} = \alpha^{(m)}_{1\to h2} + \left({}^{(s)}_{h2\to h} - {}^{(s)}_{1\to h2} \right)$$ **Equation 11-2**

Ratio method: $${}^{(m)}_{2\to h} = \alpha^{(m)}_{1\to h2} \frac{{}^{(s)}_{2\to}}{{}^{(s)}_{1\to h2}}$$ **Equation 11-3**

The superscripts *(m)* and *(s)* refer to the shears measured by the mast and sodar (or lidar) respectively. The subscripts $h_1 \to h_2$ and $h_2 \to h_h$ refer to the shears measured between the top height (1) and middle height (2) of the anemometers on the mast and between the top height and the hub height. Whichever method is used, care must be taken to avoid unrealistic or unreasonable results.

To see how such an adjustment might be applied in practice, consider the following examples.

- **Simple Case:** Suppose a 60 m tower and a sodar unit are deployed in a relatively open and flat project area. Also suppose that the shear exponent from 40 m to 60 m measured at the mast is 0.18, and that the exponent measured by the sodar is 0.20 from 40 m to 60 m, decreasing to 0.16 from 60 m to 80 m (the presumed hub height). It would be reasonable to assume in this case that the shear at all on-site towers also decreases with height. Either the ratio or difference method could be applied, and would produce a reduction of about 0.04 in the exponent at each tower.

- **Challenging Case:** Suppose a 60 m tower and a sodar unit are deployed in complex, forested terrain. The mast is near the edge of a steep drop-off, whereas the sodar is deployed 100 m back from the edge, in a clearing within deep forest. The shear exponent between 40 m and 60 m observed at the mast is 0.25, while the exponent measured by the sodar is 0.40 between 40 m and 60 m and 0.20 between 60 m and 80 m. Using the difference method, the inferred shear from 60 m to 80 m at the mast would be 0.25 + (0.20 - 0.40) = 0.05; with the ratio method, it would be 0.25 x (0.20/0.40) = 0.125. Either way, the result seems unrealistically low. It is clear that the sodar is not in a good location for interpreting the mast profile. In this case, the prudent course might be to assume a slight reduction, to perhaps 0.20, in the mast shear to hub height.

As the second example shows, direct measurements of the shear to hub height are not always easy to interpret, nor do they necessarily remove all the uncertainty in extrapolating the observed anemometer speeds to hub height. As sodar and lidar technology improves and becomes more widely used, it is likely that the uncertainties in the process will diminish.

When relying on much less than a year of direct measurements to hub height, it is important to consider seasonal variations in the wind shear as well. Where possible, only concurrent data should be compared between towers or between a tower and remote sensing system. For example, the wind shear measured by sodar over a one-month period should be compared to that measured at a tower over the same period. Because wind shear can vary widely depending on atmospheric conditions, if concurrent data are not available, it may not be possible to use the remotely sensed data at all. In general, the most accurate adjustments requires either a full year, or a statistically representative sample of a full year, of direct measurements from a hub-height tower or remote sensing system.

Displacement Height

One reason the wind shear can vary with height is if the wind flow is displaced above the ground by dense vegetation, such as a dense, closed-canopy forest. The effective ground level where the wind speed profile reaches zero is then some distance, known as the displacement height, above the actual ground level. The shear exponent calculated with respect to the displacement height d is as follows:

$$ {}^{(d)}_{1\to h2} = \frac{lo\ \frac{v_2}{v_1}}{lo\ \frac{2-d}{1-d}} = \alpha\ {}^{(g)}_{1\to h2}\ \frac{lo\ \frac{2}{1}}{l\ \frac{2-d}{1-d}} $$ **Equation 11-4**

The superscripts *(d)* and *(g)* denote the shear exponent referenced to the displacement height and ground, respectively.

Suppose that the exponent relative to the displacement height remains constant with height. Then the apparent shear with respect to ground between the top anemometer height and the hub height is given by

$$ {}^{(g)}_{2\to h} = \alpha\ {}^{(g)}_{1\to h2}\ \frac{lo\ \frac{-d}{2-d}}{lo\ \frac{}{2}} \times \frac{lo\ \frac{2}{1}}{l\ \frac{2-d}{1-d}} $$ **Equation 11-5**

(This equation is valid only for heights greater than the displacement height.) This exponent is always smaller than the observed exponent relative to ground, or in other words, the displacement effect causes the shear exponent relative to ground to decrease with height.

As an illustration, suppose the wind shear exponent measured between 40 m (h_2) and 60 m (h_1) is 0.35, and that the tower is surrounded by dense, leaf-covered trees that are 15 m tall on average. The analyst estimates a displacement height (*d*) of roughly two-thirds the tree height, or 10 m. The projected shear exponent from 60 m to the hub height (h_h) of 80 m is

$$ \mathbf{0.35}\frac{lo\ \left(\frac{70}{50}\right)}{lo\ \left(\frac{80}{60}\right)} \times \frac{lo\ \left(\frac{60}{40}\right)}{lo\ \left(\frac{50}{30}\right)} = \mathbf{0.325} $$ **Equation 11-6**

representing a 7% decrease over the observed exponent. Figure 11-1 shows the change in apparent shear relative to the ground for various combinations of observed shear exponent and displacement height for tower heights of 40 m and 60 m and a hub height of 80 m.

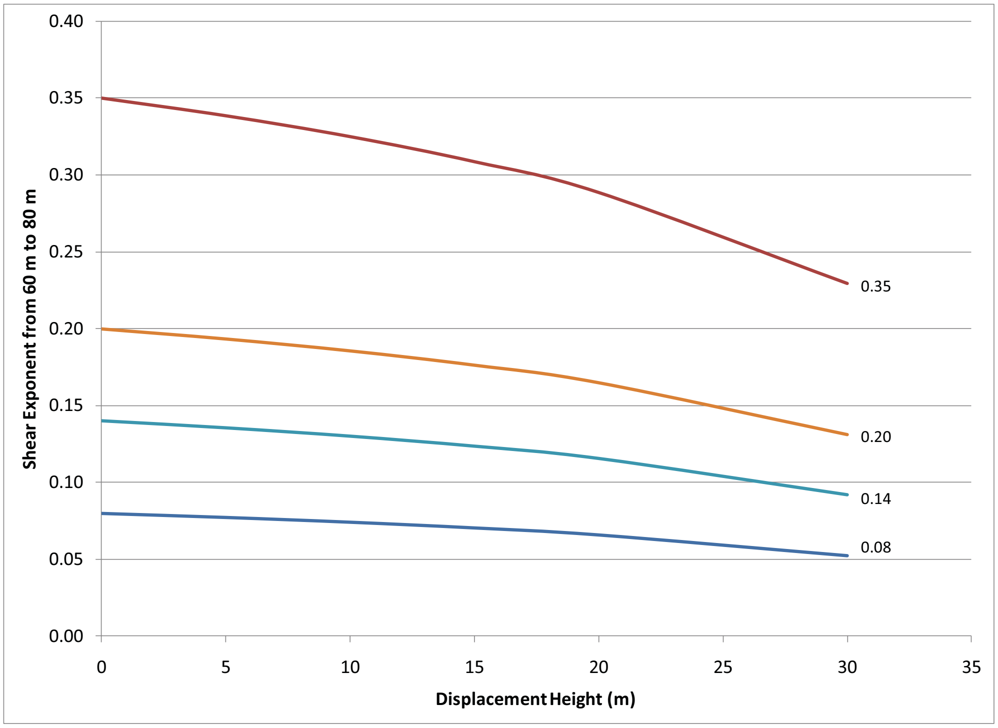


Figure 11-1 Effect of displacement height on the shear exponent between the top height of a mast and the hub height, for different values of observed shear. The observed shear is calculated between 40 m and 60 m, and the hub height is assumed to be 80 m. for each case. (Source: AWS Truepower)

The displacement height depends on the height and density of the surrounding vegetation and on the distance from the vegetation to the base of the tower. As a rule of thumb, for dense vegetation close to the tower, it is 0.6 to 0.9 times the vegetation height. [19] A directionally-weighted displacement height can be calculated if sufficient information is available; site photos can be helpful in this regard. The displacement height should be reduced as the distance between the vegetation and the tower increases. Unfortunately, there are no proven guidelines for estimating this reduction. In the absence of such guidelines, a linear reduction over a distance of 20 to 50 times the vegetation height might be reasonable.

As a practical matter, if the vegetation is no more than a few meters tall, the displacement has little impact and can safely be ignored. It is only in forest with trees more than about 10 m tall that the effect of displacement on the expected shear above the top height of the mast becomes significant.

For towers with at least four measurement heights, it is sometimes possible to dispense with displacement height and to fit the observed change in shear directly to the data. A logarithmic function often works well for this purpose. This approach is rarely feasible, however, because so few towers have as many as four levels. In addition, if the lowest level is sheltered by trees or obstacles, the fitted curve may not be reliable.

[19] J. R. Garratt, "The Atmospheric Boundary Layer," Cambridge University Press (1992), p. 290.

Convergence Height

A characteristic of the atmospheric boundary layer is that the influence of variations in topography and land cover tends to diminish with height. This idea is neatly captured in the concept of a convergence height, which is defined as the height above ground where the wind speed profiles at different points in a project area converge and the wind resource becomes homogeneous.

There is no standard or easily calculated convergence height: it varies greatly depending on the site and atmospheric conditions. In nearly flat, featureless terrain, it may be at virtually ground level, meaning the observable wind resource varies scarcely at all across the site. In complex terrain and with mixed land cover, the convergence height might be several hundred to thousands of meters above the mean ground elevation.

What is most useful about the convergence height is its corollary: near the ground, wind shear tends to be inversely related to mean speed. This is because, the greater the shear, the more rapidly the speed decreases from the convergence height down to the surface, and therefore the lower the speed at the height of measurement. (This is implied in Figure 10-1, if one imagines the convergence height is 120 m.)

The presumed inverse relationship between wind shear and speed occurs only if the shear is fairly constant with height, or at least varies with height in a similar way across the project area. This, as we have seen, does not always hold true. Nevertheless, such a relationship is observed surprisingly often, and can be used as a tool to inform judgments about the likely change in shear above a particular mast.

For example, suppose a mast has both a high shear and a high mean speed relative to other masts in the project area. It is reasonable to conclude that this shear cannot persist to a great height, as otherwise the speed profile above the mast would diverge from the others. Likewise, a mast with a relatively low speed and low shear can be expected to see an increase in shear with height. A simple scatter plot of shear exponent versus mean speed can be used to identify towers that deserve closer examination. (Note that the speeds and shears should be for the same heights and periods.) Any outliers should first be examined for poor data quality, incorrect instrument heights, or other problems that could account for the apparent discrepancy. If no such errors are found, the shear exponents for the outlying towers can be adjusted to avoid unrealistic divergence in the speed profiles. The approach is illustrated in Figure 11-2, which is taken from a wind project site in the United States. In this case, the shear at the outlying point circled in red was adjusted downward.

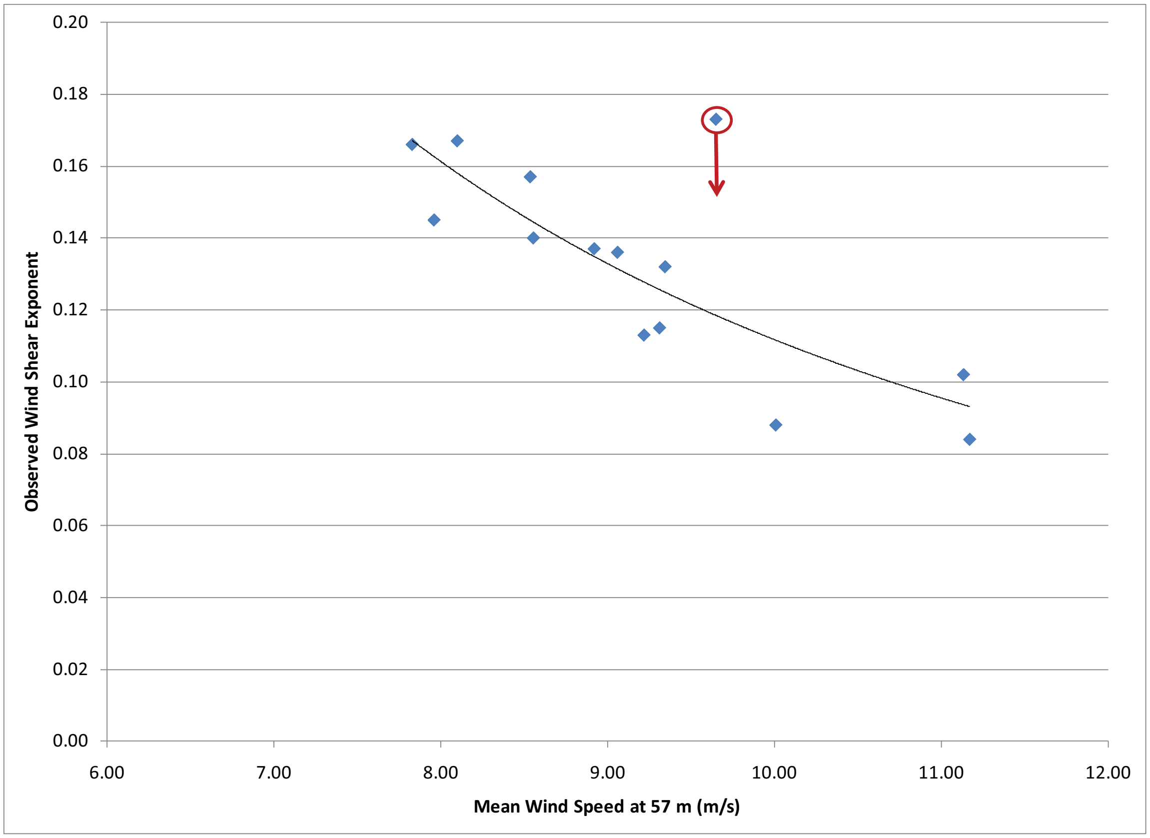


Figure 11-2 Scatter plot of wind shear versus mean wind speed at 57 m. (Source: AWS Truepower)

Logarithmic Method

The most commonly used logarithmic expression for wind shear is the following equation:

$$v_2 = v_1 \frac{lo\ \left(^2/_0 \right)}{lo\ \left(^1/_0 \right)} \qquad \textbf{Equation 11-7}$$

Here, z_0 is the surface roughness length, a parameter linked to the height and density of vegetation and other rough elements surrounding the tower.

Strictly speaking, this equation is applicable only when the boundary layer is neutrally buoyant.[20] At times of thermal stability (negative buoyancy), a more complicated form with an additional parameter, the stability length, should be used. The effect of this additional parameter is to increase the shear.

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[20] Buoyancy is defined in terms of the adiabatic rate of temperature change with height (about $6.5 \cdot 10^{-3}$ K/m). This is the rate of change in temperature of a parcel of air that is displaced upward or downward, due only to its change in pressure, with no exchange of heat with the surrounding air. If the actual temperature lapse rate exceeds this critical rate, then a parcel of air displaced upward will find itself cooler and heavier than the surrounding air, and so will tend to sink back down: it is negatively buoyant, or thermally stable. Conversely, if the lapse rate is lower than the critical rate, the atmosphere is said to be thermally unstable, and convective mixing results.

Unfortunately, the stability length must be estimated from temperature data at multiple heights, which is rarely available.

Out of convenience, therefore, most analysts rely only on the neutral form of the equation. This is important because if the roughness is determined from the vegetation (or other land cover) characteristics alone, there is a tendency to substantially underestimate the wind shear, especially in temperate climates like that of North America. Thus, z_0 must be treated as an empirical parameter that is fit to the data, much like the shear exponent. Table 11-1 indicates values of z_0 corresponding to values of α for shears calculated between 40 m and 60 m height.

α	z_0
0.08	0.0002
0.14	0.039
0.2	0.33
0.35	2.8

Table 11-1 Equivalence of z_0 for different values of α based on the power law and log law for neutrally buoyant conditions.

An important question is how the two methods compare when projecting speeds to hub height. Maintaining a constant value of z_0 is equivalent to reducing the shear exponent with increasing height. For these examples, in going to 80 m, α is reduced by about 5% to 11% in the shear range 0.14 to 0.35. The impact on the hub-height mean speed ranges from about -0.2% (α = 0.14) to -1.1% (α = 0.35).

Thus, the logarithmic approach is the more conservative. Nevertheless, while there are certainly many sites where the shear exponent decreases with height, there are many others where the shear exponent holds steady or increases. In the Great Plains of the United States, in particular, the well known nocturnal jet phenomenon (caused by a decoupling of the lower atmosphere from surface roughness under stable nighttime conditions), often produces an increasing shear exponent with height. At present, not enough research has been done to determine whether the log law or power law is the more accurate choice under most circumstances.

Overall, the differences between the two power-law and logarithmic approaches are small and largely a matter of the resource analyst’s preference. For the remainder of this chapter, only the power-law method will be discussed.

11.2. TIME SERIES OF WIND SPEEDS

While the time-averaged shear exponent is a convenient parameter for characterizing the wind resource at a site, it is not appropriate for scaling a time series of wind speed data or a speed frequency distribution. The reason is that it overlooks the wide variation in shear, and especially its dependence on direction, time of day, and time of year. Relying on an average shear can introduce errors in the speed distribution at hub height, with an impact on energy production estimates. The plot in Figure 11-3 illustrates a common pattern of variation of shear with time of day, showing a minimum during daytime hours when the atmospheric boundary layer is well mixed and a maximum at night under thermally stable conditions.

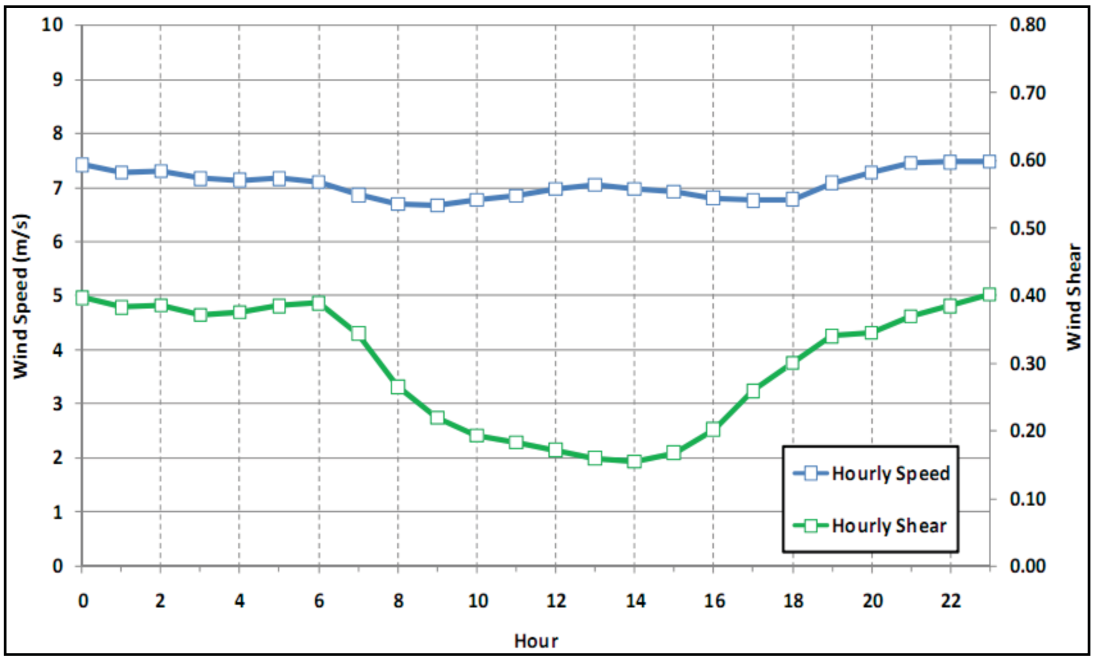

Figure 11-3 Diurnal variation of shear. (Source: AWS Truepower)

One approach to this problem is to calculate a shear exponent for each time interval (e.g., 10 minutes), and to use that exponent to extrapolate the top anemometer speed to hub height. A potential drawback of this "instantaneous-shear" method is that extreme (albeit valid) shear values can occasionally occur in the record, which may not persist to hub height. These extreme values can produce unrealistically high or low hub-height speeds; but they are generally rare. A more common problem is that shear values are available only for those records for which both the upper and lower sensors have valid data. The method cannot be applied to substituted data. Whether this is a serious problem depends on the amount of data substitution that has occurred.

As an alternative, many analysts choose to bin the speeds by direction, time of day, or time of year, or a combination of these, and to calculate the mean speed and average shear for each bin. The 10-minute wind speeds can then be extrapolated to hub height using the shear for the appropriate bin for each record. This resolves the problem of extrapolating substituted data, while preserving at least part of the full variation of shear. Care must be taken to handle bins with few or no points in an appropriate way, such as averaging speeds and shears from adjacent bins. When using this method, it is almost always important to bin by time of day to capture the effect of diurnal variations of atmospheric stability.

The time series of extrapolated wind speeds produced by either of these two methods may not have exactly the same average at hub height as that expected using the time-averaged shear. This is so even where no adjustment to the measured shear has been applied. This small discrepancy, as well as any change resulting from an explicit shear adjustment, can be resolved by a rescaling of the speeds so that the means match. The rescaling is done by multiplying each wind speed by the ratio of the expected hub-height mean speed and the mean of the extrapolated data.

11.3. OTHER PARAMETERS

Three other wind resource characteristics, the wind direction, air density, and turbulence intensity, must also be projected to hub height for estimating turbine and plant power production.

Wind Direction

It is generally assumed that the wind direction is constant with height above the top anemometer. This is not strictly true even in principle, as the interaction of the earth's rotation with frictional and pressure forces tends to produce a rotation of the wind vector with increasing height above ground. This effect, however, is quite small, so a constant direction is usually a safe assumption. Therefore, the directions recorded at the top anemometer vane (with substitutions as needed) are generally projected to hub height with no alteration.

There are sites where, because of the influence of terrain or strong temperature gradients, substantial directional changes with height (veer) are frequently observed. Such shifts can reduce turbine power production since the wind vector may not be perpendicular to the rotor throughout the rotor plane. Remote sensing using sodar or lidar can detect these situations.

Air Density

Two factors affect how the air density varies with height: the pressure (or elevation) and air temperature. The air temperature is usually extrapolated from the thermometer height to the hub height using the temperature lapse rate of the standard atmosphere of 6.5 ºC (K) per 1000 m. For a thermometer height of 3 m and a hub height of 80 m, this represents a drop in temperature of about 0.5 ºC. Applying the change in temperature and height to the density equation, the effect is to decrease the air density by about 1.1% (independent of elevation).

Turbulence Intensity

The TI at hub height is normally estimated by assuming that the 10-minute speeds decrease with height above the top anemometers while their standard deviations remain constant. Thus, the TI for each record decreases with height, and the speed-averaged TI follows suit. The mean TI for the 15 m/s bin - a standard reference parameter for determining if a particular turbine model is suitable for a site - may change slightly, if at all.

Section 12

12. THE CLIMATE ADJUSTMENT PROCESS

The last major step in characterizing the wind resource at a wind monitoring station - before extrapolating it to the wind turbine locations - is to adjust the observed wind climate to the historical norm. Average wind speeds can vary substantially from the norm even over periods of a year or longer. For example, the uncertainty in the long-term mean wind speed, based on a year of measurement, is typically about 3-5% [21], corresponding to perhaps 5-10% in the mean wind plant production - a significant factor when assessing the risk of financing a wind project. Reducing this uncertainty is the primary goal of the climate-adjustment process.

The leading method for performing climate adjustments is popularly called MCP, which stands for measure, correlate, predict. The wind resource is measured at a site (sometimes called the target) over a period ranging from several months to several years. The observed winds at the target site are correlated with those recorded at a long-term reference, such as an airport weather station, and a relationship between them is established. Then, the much longer historical record from the reference is applied to this relationship to predict the long-term mean wind resource at the target site. An example of the relationship between the periods of record for a reference site and a monitoring mast is provided in the Figure 12-1 below.

That is how the process is supposed to unfold, and often it does so successfully. Complications sometimes arise, however, and the accuracy of the resulting long-term wind resource estimates depends on how they are handled.

Chapter 12 At-a-Glance

- The key assumption underlying the MCP process is that the wind climate is stable. Research suggests that moderate changes may occur in the future, but their impact during the lifetime of a wind project investment is likely to be small compared to other sources of uncertainty.
- To be successful, MCP requires that the site correlate well with a long-term reference station, that the reference station have a homogenous wind speed record, and that the site and reference records overlap for at least 9-12 months.
- A number of different target-reference relationships can be used, including linear regressions, non-linear equations, and matrix methods. Each has strengths and weaknesses.
- An unconstrained linear regression is relatively simple to apply and generally provides a good estimate of the long-term mean speed so long as the MCP criteria are met. To estimate the long-term speed frequency distribution, however, other methods must generally be used.

[21] Based on an analysis by AWS Truepower of data from first-order meteorological stations in North America. At some locations, the interannual variability may be larger than 4%.

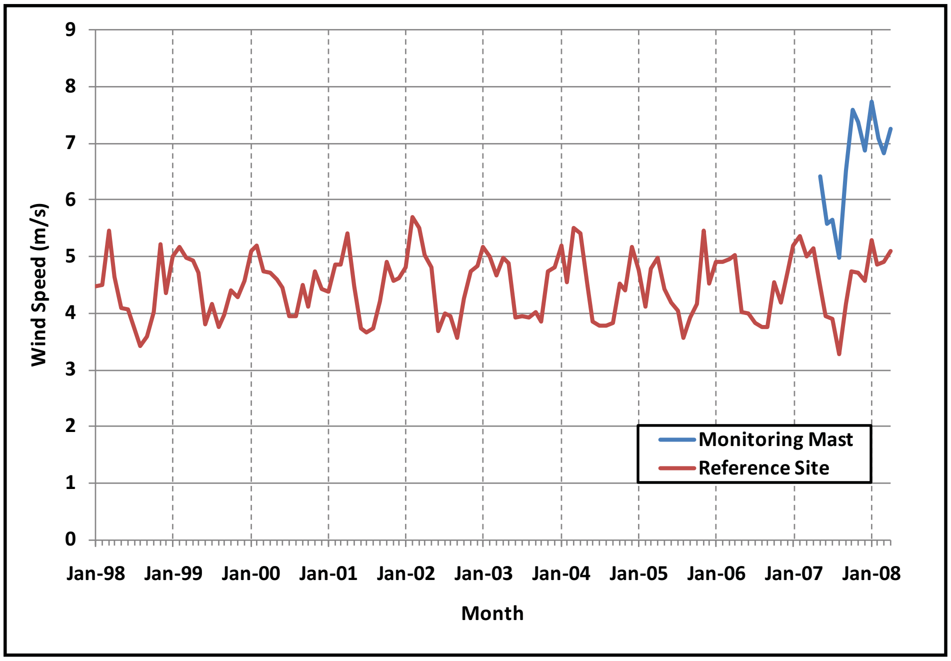

Figure 12-1 Example period of record for a reference site and a monitoring mast.

This chapter addresses, first, the assumptions underlying MCP; second, the requirements that must be met for successful MCP; third, the data sources most widely used for MCP, including their advantages and pitfalls; and last, various methods of relating winds observed at the target and reference and of predicting the long-term wind resource.

12.1. IS THE WIND CLIMATE STABLE?

The key assumption underlying all MCP methods is that the wind resource in the future will be similar to what it has been in the past - in other words, that the wind climate is stable. In this age of climate change, it is reasonable to ask whether this assumption holds true, and what its implications might be for the accuracy of energy production forecasts. Even in the absence of climate change linked to greenhouse-gas emissions, the possibility of other sources of change in a site's wind climate, including cyclical weather patterns such as the El Niño Southern Oscillation (ENSO) and local factors such as urbanization and changing vegetation cover, must be considered.

Historical Evidence

Historical evidence concerning the long-term stability of the wind climate is mixed. A key problem is that there are few wind monitoring stations where the wind has been measured continuously (at the same height and at the same location, with consistent measurement protocols, and using the same instrument or instrument type) for more than 10 to 15 years. Since the annual mean wind speed varies significantly from year to year, the dearth of truly homogeneous long-term data sets makes it difficult to distinguish a trend caused by climate change or other processes from one that is the result of normal fluctuations.

Various researchers have nonetheless attempted to detect changes in wind resources over time. The following examples illustrate the difficulties:

- An examination of global reanalysis data - the product of a global weather model driven by historical weather observations - from 1974 to 2004 revealed both moderate decreases and moderate increases in the mean annual wind speed (from -0.2 to +0.2 m/s per decade) in different parts of North America. Some of these patterns are not confirmed by reliable observations, however, and are probably caused by changes in the observational platforms and protocols used to create the reanalysis data set (such as the introduction of weather satellites in the 1970s and 1980s).[22]

- An examination of surface observations from weather stations reveals an unambiguous decline in mean wind speeds in the United States since 1973. It seems likely that the advent of the Automated Surface Observing System (ASOS) in the mid-1990s, as well as other changes such as urbanization and tree growth, are responsible for much of this decrease. The authors of this study note, "We did not attempt to correct for these inhomogeneities, but their presence strongly argues for use of the other data sets..." By and large, the other data sets they mention - mainly reanalysis data sets - do not support the observed decline in surface wind speeds.[23]

- Rawinsonde (instrumented balloon) data for North America show an *increasing* trend in mean annual wind speeds at a pressure height of 850 hPa (about 1500 m above sea level) from 1987 to 2006; this follows a decreasing trend in the previous two decades.[24]

On balance, there are no grounds for concluding that the wind resources in North America have either increased or decreased significantly in the past several decades as a result of climate change. Considering the uncertainties in the data, any changes that have occurred are below the level of confident detection.

Prospects for Change in the Future

What about the future? Although the results of research are far from definitive, overall they point to a probable moderate decrease in wind resources in North America over the next 50-100 years:

- A study drawing on the results of two general circulation models (GCMs) - global weather models used by climate researchers to predict climate change - under a single scenario of future greenhouse-gas levels suggested that mean annual wind speeds over the lower 48 states could

[22] Brower, M.C., et al., "Impacts of Global Climate Change on Wind Resources: The Historical Case," Poster presentation at Windpower 2005, May 2005.
[23] Pryor, S.C., et al., Wind speed trends over the contiguous United States, Journal of Geophysical Research, Vol. 114, D14105, doi:10.1029/2008JD011416, 2009.
[24] Freedman, J. M., and J. W. Zack, 2007: Climate and Wind Energy: Outlook for Wind in a World Undergoing Climate Change—Recent Trends in Wind Speed. Wind Power 2007, June 2007.

decrease from 1.0% to 3.2% by 2050 and from 1.4% to 4.5% by 2100, compared to a 1948-1975 baseline. The two models disagree strongly over the magnitude of the reduction, indicating substantial uncertainty in the conclusion. [25]

- Researchers applied a statistical "downscaling" method to four GCM models under two greenhouse-gas scenarios and projected the impacts of climate change at five weather stations in the Northwestern United States. They found that mean wind speeds at these stations could decrease by amounts ranging up to 10%, depending on the station and time of year, with the greatest reductions occurring in summer at most sites. The results were fairly consistent across models and scenarios. [26]

- A high-resolution numerical weather prediction model was used to downscale a single GCM model and greenhouse-gas scenario over southern California. This study found a pattern of both moderate increases and decreases in mean wind speed in 2041-2060 compared to 1980-1999. Unlike other studies, this one looked specifically at an area where wind projects are operating: Tehachapi Pass. A 2-4% decrease in the mean annual wind speed was predicted where the wind projects are concentrated. Most of this decrease occurred from fall to winter; relatively little change was forecast for the main power-producing months of April to August. [27]

Still, based on the historical evidence and modeling studies to date, any changes in the wind climate over the time horizon of wind project investments - up to 25 years - are likely to be modest. Even a 5% decrease in the mean annual wind speed over 50 years, if it occurred in a linear fashion, would result in only a 0.5% decrease in the average resource over the first 10 years of a wind project's life. More likely, as some studies have indicated, the pace of change will initially be smaller. For this reason, and for the time being, the "climate-change risk" for wind project investments appears to be small compared to other sources of uncertainty in wind resource assessment.

Other Factors That May Affect the Local Wind Climate

Other factors besides climate change linked to greenhouse gases could alter the future wind climate at a project site. Among these are cyclical weather patterns, including most famously the El Niño/Southern Oscillation (ENSO), but also less well known phenomena such as the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO). ENSO events - which are the most influential - last from six months to two years and occur in cycles of roughly every four to six years. Although ENSO's root causes

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[25] Breslow, P.B., and D. J. Sailor, Vulnerability of wind power resources to climate change in the continental United States, Renewable Energy 27 (2002), 585-598.

[26] Sailor, D. J., M. Smith, and M. Hart, Climate change implications for wind power resources in the Northwest United States, Renewable Energy 33 (2008), 2393–2406.

[27] Freedman, J. M., Final Report: Effects of Climate Change on Production of Electricity from Wind Power in California (2009).

are in some dispute, the phenomenon is closely tied to wind-driven variations, or anomalies, in surface water temperatures in the eastern Pacific Ocean. These temperature anomalies have a substantial impact on weather patterns around the Pacific Rim and throughout the world.

To minimize any effects of such cyclical patterns through MCP, the reference station record should span at least two or three oscillation periods. For ENSO, that means around 10 to 15 years - a feasible time horizon for most MCP studies in North America. Because of problems in older reference data sets (described in a later section of this chapter), it is far more challenging to correct for the Pacific Decadal Oscillation, with a period of 20 to 30 years, and other very long-period phenomena. Considering that the period of these oscillations is comparable to - or exceeds - the time horizon of wind plant investments, and that their behavior cannot be reliably forecast, it is arguable whether such corrections should even be attempted.

Changes in land cover around a site, especially tree growth or clearing, can also alter the wind climate. Considering only the displacement effect of a forest very near the turbines, a typical tree growth rate of 0.2 m per year could reduce the mean wind resource at 80 m height by perhaps 0.5% by the end of the first 10 years of a project's life. This impact is comparable in magnitude to possible trends from global climate change, but unlike climate change, it should be easily forecast based on assessments of the forest condition. Conversely, the clearing of 10 m trees around turbines could *increase* the available wind resource by up to about 2%, depending upon the size of the clearing. Both types of impact could be larger if the changes occurred over a much wider area - up to several kilometers - surrounding the project.

12.2. REQUIREMENTS FOR ACCURATE MCP

Assuming the wind climate is stable, three key requirements must be met for MCP to produce a reliable result:

- The site and reference station must be in substantially the same wind climate. This means that variations in wind speed at each location should be well correlated in time. The correlation can be assessed qualitatively by plotting a time series of observed wind speeds for both the target and reference stations. A quantitative measure such as the Pearson correlation coefficient (r) can also be used. The square of the correlation coefficient, r^2, is can be thought of as the fraction of the variation in the values of one variable that can be explained by a linear equation with another variable.

- The target and reference station must have a homogenous wind speed record. A wind speed record is said to be homogeneous if the measurements have been taken continuously at the same location and height with equivalent instrumentation. In the case of the reference station, its record should be substantially longer than, and overlap with, that of the target site.

- The concurrent target-reference period should capture seasonal variations in the relationship. In practice this means at least nine continuous months, and preferably a year or more.

It will become clear in the following sections that the first two requirements, in particular, are not always easy to satisfy.

Correlation

When a wind project site is in flat, open terrain, it is often easy to find a weather station in the vicinity that experiences much the same wind climate. This is true especially of the Great Plains of the United States and Canada. In other parts of North America, however, it is not uncommon for the available reference stations to be in quite different wind climates. For example, the project site may be on an exposed ridge or mountain top, while the nearest reference stations are all in sheltered valleys; or the project site may be near a coastline while the available reference stations are well inland. The result can be relatively poor correlations between the target site and reference station (Figure 12-2).

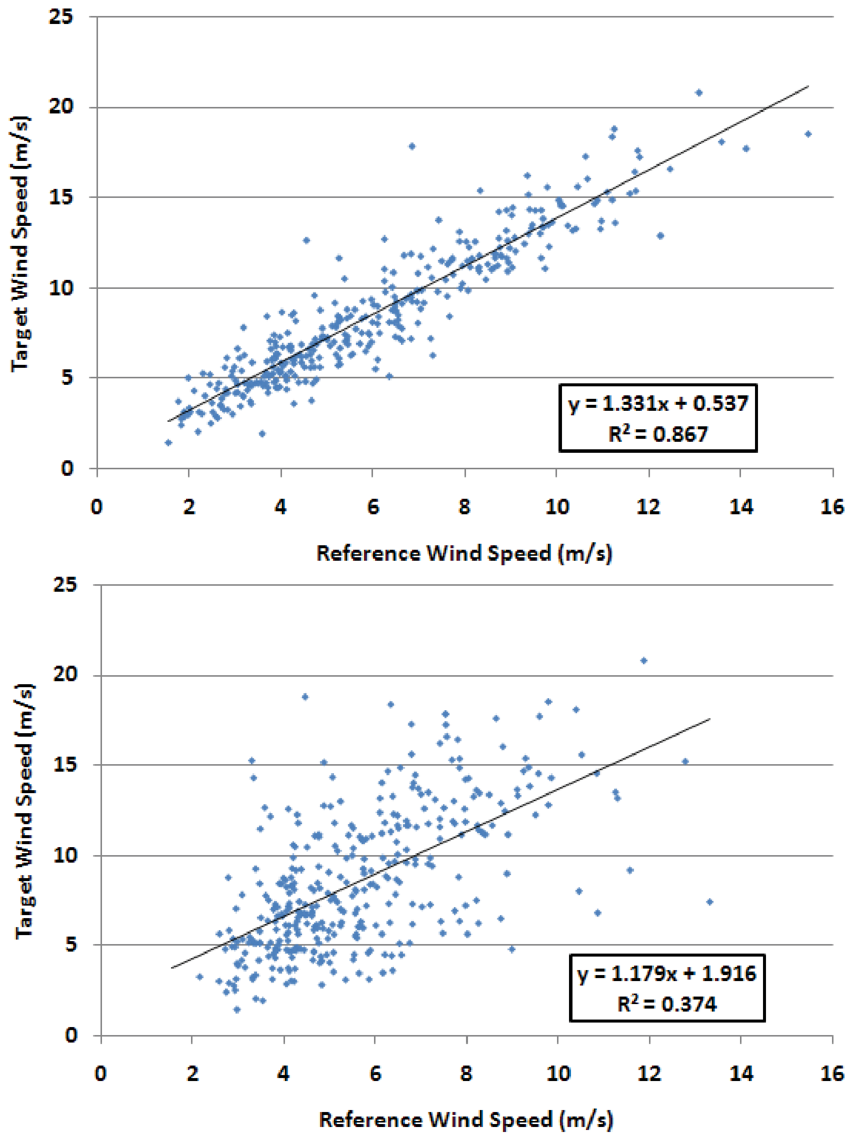

Figure 12-2 Typical scatter plots of target and reference wind speeds. The upper plot shows a relatively high r^2 value, indicating the two sites experience very similar wind climates, whereas the lower plot shows a relatively poor correlation. (Source: AWS Truepower)

The weaker the correlation with the reference station, the larger the uncertainty in the adjusted long-term wind resource at the target site. Assuming normally distributed annual wind speed fluctuations and a homogeneous reference station data record, the following simple equation approximates the overall uncertainty in the long-term mean wind speed as a function of the correlation coefficient, r^2:

$$\sigma = \sigma_A \sqrt{\frac{r^2}{N_R} + \frac{1-r^2}{N_T}}$$ **Equation 12-1**

Here, σ_A is the standard deviation of the annual mean wind speed as a percent of the mean; for simplicity, it is assumed to be the same for the reference and target sites. An analysis of ASOS data indicates this value is typically around 3-5%; although some wind farms may experience more or less interannual variability than observed at these airport stations. N_R is the number of years of reference data, and N_T is the number of years of concurrent reference and target data. (Because of seasonal effects, this equation should not be used if $N_T < 1$.)

The chart in Figure 12-3 plots this equation as a function of r^2 for the observed range of values of σ_A. One year of concurrent reference-target data is assumed. Looking at the middle curve, when there is no correlation, the error margin simply equals the annual variability, in this case 4%. For mid-range values of r^2, the MCP process reduces the uncertainty by one-fourth, to about 3%. If the correlation is very high, the uncertainty is reduced by nearly 70%, to 1.3%. As this chart suggests, there is usually no point in employing a reference station with less than a 50% r^2 value; many resource analysts do not consider stations with values of r^2 below 60-70%.

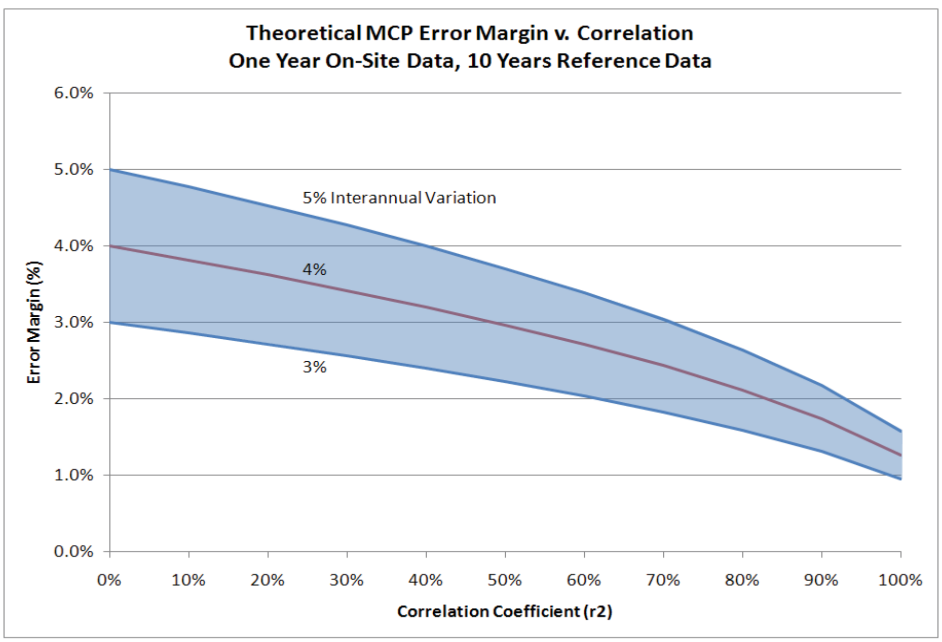

Figure 12-3 Uncertainty margin in the estimated long-term mean wind speed at a site, assuming one year of on-site data and 10 years of reference data, as a function of the r^2 coefficient between them and of the interannual variation in the wind at the site (the standard deviation of annual mean wind speeds divided by the long-term mean). (Source: AWS Truepower)

An important question is what averaging interval should be applied to the wind speeds when using the MCP process. The optimal averaging interval for MCP is related to the time scale at which wind fluctuations may be experienced *simultaneously* by the reference and target sites. If the interval is too short, then a large proportion of the speed fluctuations may contain no useful information about the relationship between the two stations; they are just noise. If the interval is too long, on the other hand, then important information about the relationship may be lost.

The optimal time interval is, in turn, related to the size of typical weather disturbances and their rates of motion. As a rule of thumb, the duration of a wind "event" - whether it is a gust occurring in a matter of seconds or a sustained period of high winds lasting several days - approximately equals the size of the associated weather disturbance (which may range from a small turbulent eddy to a large storm system or front) divided by its speed relative to the observer. A wind fluctuation cannot occur simultaneously at two points unless both are within the realm of influence of the same disturbance. Thus, the shortest time scale over which *correlated* fluctuations can occur, Δt, is, very approximately, the distance between the target and reference stations, D, divided by the typical or average background wind speed, v:

$$\Delta t \approx \frac{D\,(\ m)}{v\left(\frac{m}{s}\right)}\,(s)$$ **Equation 12-2**

Suppose the typical mean wind speed is 7 m/s. Then the shortest reasonable time scale to correlate stations that are, say, 100 km apart is about 14285 seconds, or four hours.

As a general guideline, when the reference is an ordinary surface weather station located some distance away from the target tower, daily averaging serves well. This has the advantage that it is simple to apply and it reduces the influence of differences in diurnal wind speed patterns related to tower height and station location (which can also introduce noise in the correlation). The only time a shorter interval such as one hour or 10 minutes might reasonably be used is when the reference station is within a few kilometers of the target site. This occurs most often when secondary masts are correlated with a primary reference tower within the project area.

Homogeneous Wind Speed Observations

The requirement for a long, homogeneous reference data record can also be difficult to meet. One problem is that measurement standards change from time to time as national weather agencies seek to improve their measurement technology and data products. Unfortunately, this runs counter to the wind industry's interest in having consistent, long-term wind data sets. In the United States, for example, almost all leading weather stations were converted to the Automated Surface Observing Systems (ASOS) standard in the middle to late 1990s and early 2000s. In the process, tower heights changed from (typically) 6.1 m to 10 m, many towers were moved, and the previous manual recording technology was replaced by automated digital equipment. The result was such a large and unpredictable discontinuity in the recorded wind speeds that data collected before the date of ASOS installation became effectively useless for MCP.

More recently, cup anemometers, which have been the standard for many decades at U.S. weather stations, were replaced by ultrasonic anemometers, resulting in another disruption in the continuity of wind speeds. Fortunately, the impact of this change was not as severe as that which occurred with the deployment of ASOS. Since there has been no change to the monitoring heights, locations, or data collection practices, adjustment factors can be applied to compensate for the effects of the anemometer change at most ASOS stations. Still, there is additional uncertainty associated with this adjustment, which must be considered before using these stations. In some cases, this incremental uncertainty will result in a total MCP uncertainty that is higher than if the on-site data were used alone. In this case, the adjusted ASOS data should not be used.

Another challenge is changing site conditions around reference stations, which can create false trends in wind speeds. Figure 12-4 shows an extreme case: a downward trend in observed speeds starting around the middle of the 20th century at Blue Hill Observatory in eastern Massachusetts. This trend - which does not appear in other weather records in the region - is at least partially attributable to the re-growth of previously cleared forest around Great Blue Hill, as suggested by the photographs.

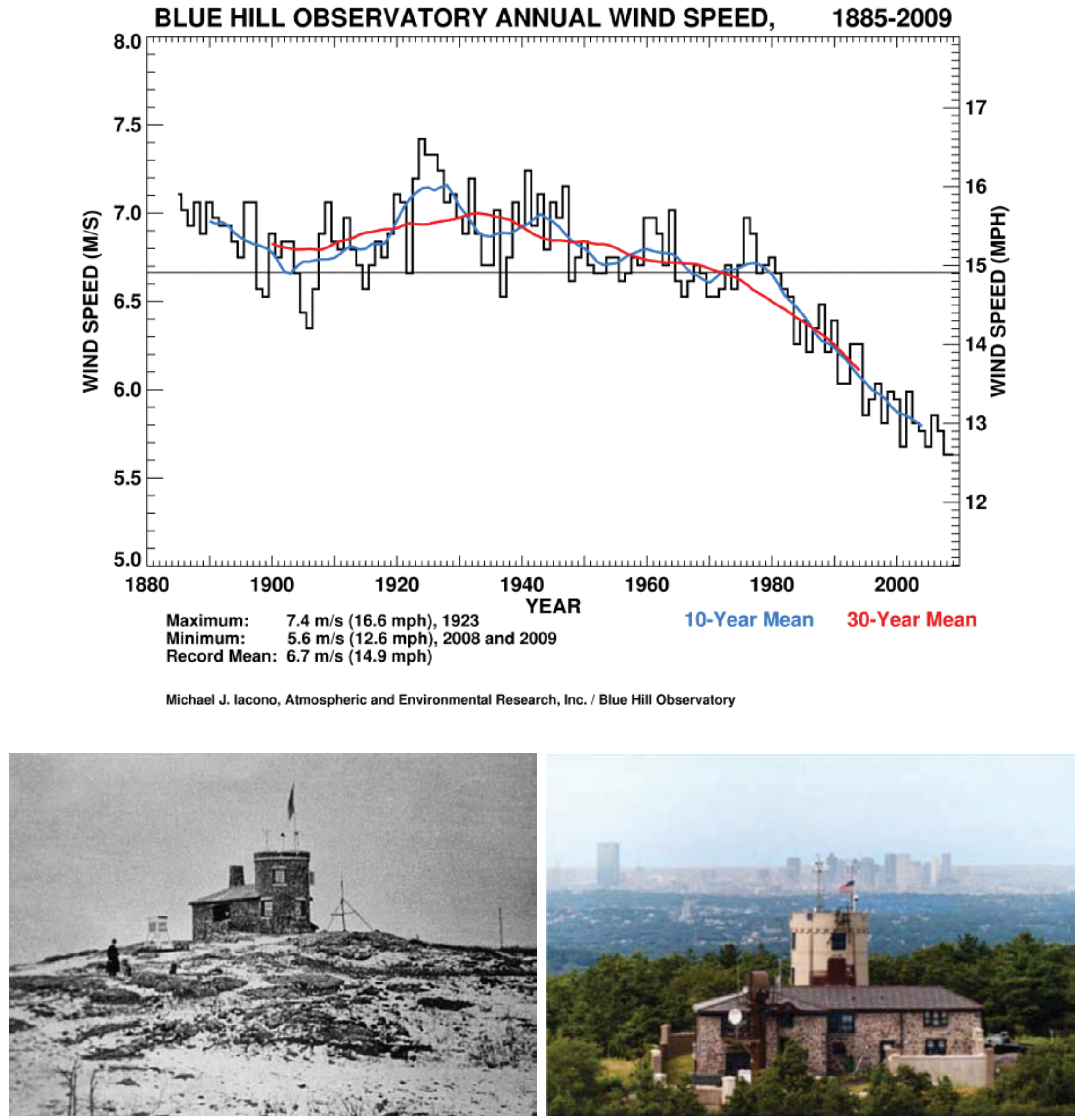

Figure 12-4 *Top*: Wind speeds recorded at the Blue Hill Observatory outside Boston. *Bottom*: Photographs of Blue Hill Observatory taken in 1886 (left) and present day (right). (Source: Blue Hill Observatory – www.bluehill.org)

In the absence of significant trends or discontinuities, the uncertainty in the long-term mean wind speed derived through MCP should decrease as the length of the reference station's record increases; but only to the extent the two stations are correlated in time. This is what Equation 12-2 says: the longer the reference data period, the better. In most real-world situations, however, the benefit of going beyond about 10-15 years of reference data is limited. Figure 12-5 shows the uncertainty for a range of values of r^2 (from 0.45 to 0.95) and N_R (from 1 to 30 years) based on the same equation, and assuming $N_T = 1$ and $\sigma_R = \sigma_T = 4\%$. The two dashed curves mark the points where 80% (left-hand curve) and 90% (right-hand curve) of the maximum possible reduction in uncertainty is achieved. For all reasonable values of r^2, 80% of the maximum benefit is reached with less than 10 years of reference data. For $r^2 \leq 0.85$, 90 % of the benefit is reached with less than 17 years of data.

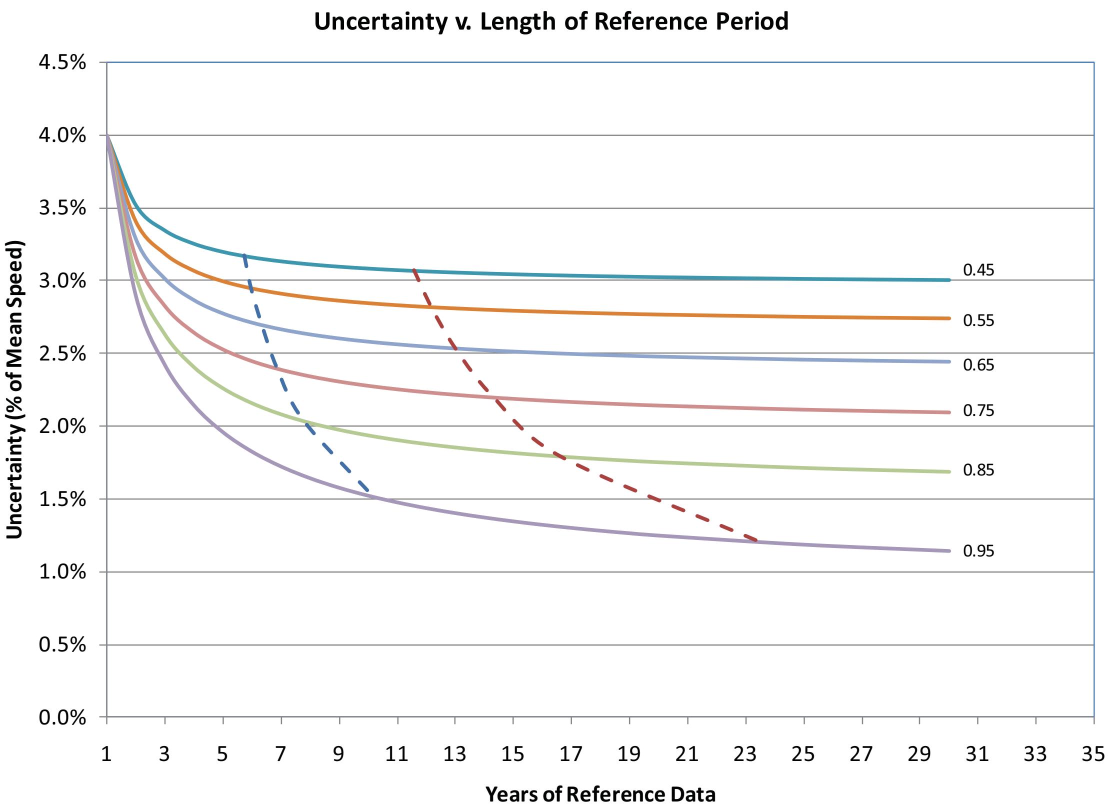

Figure 12-5 Plot of the statistical uncertainty in the long-term mean annual wind speed at the target site as a function of number of years of reference data and for different values of r^2. The two dashed curves show the number of years required to achieve 80% (left-hand dashed curve) and 90% (right-hand dashed curve) of the maximum possible reduction in uncertainty. The curves are derived from the equation in the text, assuming 4% inter-annual wind speed variation, one year of overlapping reference and on-site data, and no significant trends or discontinuities in the reference data set. (Source: AWS Truepower)

The presence of trends or discontinuities in the reference data - whether artifacts of changing site conditions or measurement techniques, or real manifestations of climate change - can have a pernicious effect on the accuracy of MCP. Suppose there is a linear trend in the reference wind speed. If the trend is not real - perhaps trees are growing around the station, or perhaps the anemometer has been slowing down because of wear in the bearings - then the adjusted long-term mean wind speed will tend to be biased by an amount that depends on the slope of the trend line and the length of the reference data record:

$$\varepsilon \approx -\frac{N}{2} s \ (\%) \qquad \textbf{Equation 12-3}$$

Here s is the trend slope in percent per year, and N is the number of years in the reference data record. (In this equation, one year of overlapping on-site and reference data and perfect correlation between them is assumed.) Thus, where false trends are present, the magnitude of the potential bias increases with the length of the reference period. The problem is compounded if the trend is caused by a real and persistent change in climate - in other words, if the assumption of climate stability is violated. Then the bias resulting from the ordinary MCP process may be even larger, if the trend continues in the future.

Thus, MCP - while still a mainstay of wind resource assessment - cannot remove all uncertainty in the long-term wind climate, and must be applied with considerable caution. The following practical guidelines are offered:

- The net should be cast widely for potential reference stations and data sources. The more data sets available for analysis, the easier it is to detect inhomogeneities.
- The data recovery rate at the reference stations should be high and consistent over time. Long gaps or significant changes in the data recovery render the data homogeneity suspect.
- The available documentation for each station should be examined carefully to determine whether its instruments, tower height, location, or measurement protocols have changed. The reference period should be the most recent period for which conditions at the station have remained substantially the same.
- The reference data for each station should be assessed visually and statistical tests applied where appropriate to detect trends or inhomogeneities larger than can easily be explained by normal fluctuations.
- The resource analyst should be wary of reference data records extending back more than 15 years, even if there has been no documented change in the station equipment or protocols. There is little confidence that measurements (or modeled data sets such as reanalysis data) as old as this are representative of the more recent local wind climate.
- The analyst should be skeptical of MCP adjustments - especially upward adjustments - of more than 3-4% based on a year or more of on-site data, as they may reflect problems in the reference data.

12.3. SOURCES OF REFERENCE DATA

Most sources of reference data fall into one of four general categories: tall towers instrumented for wind resource assessment, surface weather stations, rawinsonde stations, and modeled data sets. The Appendix provides information on how to obtain data from these various sources in North America. This section discusses some of the pros and cons of each data source and provides guidance on how they should be used.

Tall Towers Instrumented for Wind Resource Assessment

It is unusual, but not impossible, to obtain data from tall towers with a sufficiently long record to be useful as reference data sets for MCP. Wind monitoring programs have been carried out in several US states, and data from some of these towers are publicly available. So long as the data prove to be well correlated with the target site and homogeneous through time, they can be an excellent source of reference data. The analyst should be aware of gaps in the data record (caused quite often by interruptions in the financing of the wind monitoring programs), as well as possible changes in the anemometers and anemometer mountings. The possibility that wind turbines may have been installed near the tower (a distinct risk given that many such towers are in areas of good wind resource) should also be verified. If the nearest upwind turbine is closer than about 20 rotor diameters to the mast, then the data may not be usable. It is also wise to mistrust published data summaries and pre-processed data files. Whenever possible, the raw data from the towers should be obtained so the analyst can carry out their own quality control.

Surface Weather Stations

The mainstay of MCP remains surface weather stations. In the United States, ASOS stations are generally preferred for MCP because they are well documented, and – with the exception of the replacement of cup anemometers by "ice-free" ultrasonic, or IFW, anemometers – their instrumentation, maintenance, and data-recording protocols have remained consistent since the ASOS installation date. There are approximately 900 ASOS stations in the United States. Although their geographic distribution is uneven, they provide reasonably good coverage in most parts of the country. Archived wind speed and direction data are available on one-minute, five-minute, and an hourly basis. For the hourly observations, each speed value is not a true hourly average, but represents a two-minute average some minutes prior to the top of each hour. Thus, even if a station is very near a wind project site, a very good correlation of hourly wind speeds should not be expected, and daily means should be employed instead. If a significant portion of the target data were recorded after the installation of IFW anemometers, then an adjustment should be applied to correct the IFW data to the cup anemometer baseline.

Figure 12-6 The ASOS station at Albany Airport, Albany, New York. (Source: NOAA)

Although most ASOS stations provide a fairly consistent picture of wind speed trends in their respective regions, some may be influenced by encroaching urbanization or (especially in the eastern United States) reforestation. The homogeneity of each station's data record must be evaluated case by case - usually by comparing trends from different stations in the same region. Plotting the ratio of monthly or annual mean wind speeds for different pairs of reference stations can be very useful for spotting suspicious trends. Where two apparently reliable stations exhibit different trends, one upward and the other downward - and no other stations are available for comparison - it is usually the safer course to reject the downward-trending station, since few problems with surface stations are likely to cause an increase in speed.

Other surface weather stations tend to be less reliable and less well documented, and are usually best avoided unless no suitable ASOS station is available. Among these secondary data sources are stations in the National Weather Service Cooperative Surface Station network, Automated Weather Observing Systems (AWOS), Remote Automated Weather Stations (RAWS), as well as privately-funded general weather data collection networks.

Rawinsonde Stations

Data from instrumented weather balloons (Figure 12-7), known as rawinsonde stations, can sometimes be useful for MCP. One advantage of rawinsonde observations is that they are generally taken well above the land surface (at both fixed and variable heights defined by atmospheric pressure) and so are largely insulated from changes in land cover. Another is that they can be at or near the height of high ridge-top wind project sites, and thus may provide a better correlation with the target tower than relatively sheltered surface weather stations. The lowest mandatory monitoring levels are at 1000 mb, 925 mb, 850 mb, and

700 mb, which span the vertical profile from near sea level to roughly 3000 m. In addition, there are several fixed altitudes where wind speed and direction data are required to be reported. [28]

Figure 12-7 A weather balloon used for making soundings in the atmosphere. (Source: NOAA)

They also have disadvantages: There are far fewer rawinsonde stations than surface stations, meaning that the nearest rawinsonde station is often much farther away from the project site than the nearest surface station. In addition, the balloons are launched only twice a day, at 12:00 noon and midnight Universal Coordinated Time, or UTC (also known as Greenwich Mean Time). (These days, some weather balloons are launched four times a day, but this practice is relatively recent, and thus the two extra observations must usually be discarded to ensure a homogeneous long-term data set.) With so few observations, a correlation based on daily mean speeds may yield a poor result, and therefore weekly or monthly means may be called for. This substantially reduces the amount of independent information available for establishing the target-reference relationship.

Despite these disadvantages, it is often a good idea, especially for projects in complex terrain, to obtain rawinsonde data for two or three stations either for direct use in MCP or for verifying the homogeneity through time of available surface weather data.

Modeled Data Sets

In recent years the use of reference data sets created by atmospheric models has become more common, though it is not yet the industry norm. The most well known type of modeled data is called reanalysis data. It comes in several varieties and is produced by a number of national weather agencies, including the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR), and the European Center for Medium-Range Forecasts (ECMWF). The NCEP/NCAR data are available free of charge, and therefore tend to be the most widely used.

All reanalysis data sets are created by using historical weather observations (generally from surface, rawinsonde, satellite, and aircraft-borne instruments) to drive a global or regional numerical weather prediction (NWP) model. From these model runs, weather parameters (including temperature, pressure, wind, precipitation, and many others) are extracted for every grid point and every level in the model. Reanalysis data sets were created to support climatological studies because real-time weather models are

[28] Federal Meteorological Handbook No.3, Rawinsonde and Pibal Observations, Office of the Federal Coordinator for Meteorology, 29 May 2007

constantly being improved, making it difficult to use them to establish a consistent climate record, whereas the models used for reanalysis are fixed for the entire historical simulation.

Reanalysis data have a number of positive attributes, including convenience, multiple levels and types of weather parameters, and a long data record (more than 60 years for some data sets). Because the gridded data are available everywhere covered by the model, there is no difficulty finding a nearby grid point. This eliminates much work searching for surface weather stations and data sets, and it provides a common data source for all MCP studies. In parts of the world where surface weather observations are unreliable, reanalysis data may be the only feasible source of reference data for MCP.

Reanalysis data also have significant disadvantages, however, and must be used with caution. First, the correlation of the reanalysis winds with tower observations depends on the complexity of the terrain and the resolution of the reanalysis model. The NCEP/NCAR global reanalysis data set, in particular - the most widely used - is relatively coarse with a resolution of about two degrees in latitude and longitude (a little over 200 km), and thus may give poor results in mountainous terrain, at coastal boundaries, and other places where there is a sharp wind gradient.

More important, the homogeneity of reanalysis data is limited by that of the observational system used to drive the model, which has changed dramatically over the decades. The bulk of the weather observations in the 1950s and 1960s came from weather balloons supplemented by land and ship-based surface observations. Weather satellites became increasingly important in the 1970s and 1980s, decades that were marked also by the retirement of weather ships, growth in the use of commercial aircraft to supplement weather observations, and a large increase in the frequency of weather observations from both surface and rawinsonde stations. The importance of these changes is suggested by Figure 12-8, which charts the variations in total megabytes of data from various global rawinsonde, aircraft, and surface observational databases.

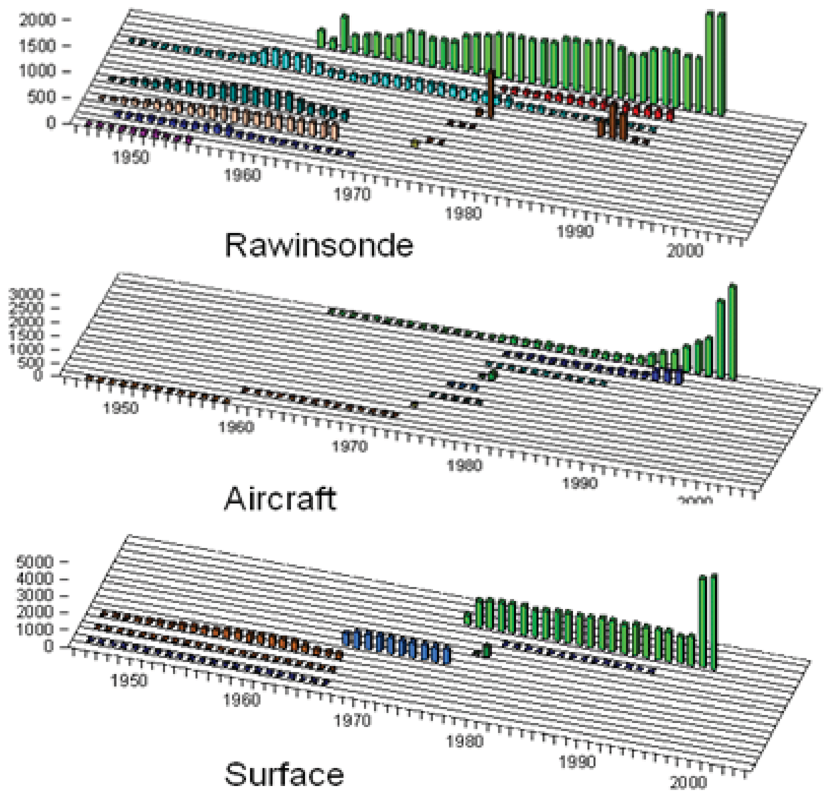

Figure 12-8 Total megabytes of data ingested annually by the NCEP/NCAR global reanalysis model from the 1940s to the 1990s. Each row represents a different data set; the back (green) row refers to data maintained by NCEP. [29]

To some degree, the atmospheric model should be able to attenuate the impact of such changes as observations from one new platform or sensor are reconciled with those available from existing sensors. At different times and in different regions, however, the availability of new data can significantly alter the model's analysis, resulting in spurious trends and shifts in wind and other parameters.

Figure 12-9 provides a clear example of such a problem with the NCEP/NCAR global reanalysis winds over Denver, Colorado. More broadly, as Figure 12-10 illustrates, the NCEP/NCAR global reanalysis surface winds exhibit a slight downward trend in the past 10 years, which is not present in ASOS observations, while the mean winds from another reanalysis data set, North American Regional Reanalysis, suddenly jump in 2002.

[29] Robert Kistler et al., The NCEP/NCAR Reanalysis, Bulletin of the American Meteorological Society (2001)

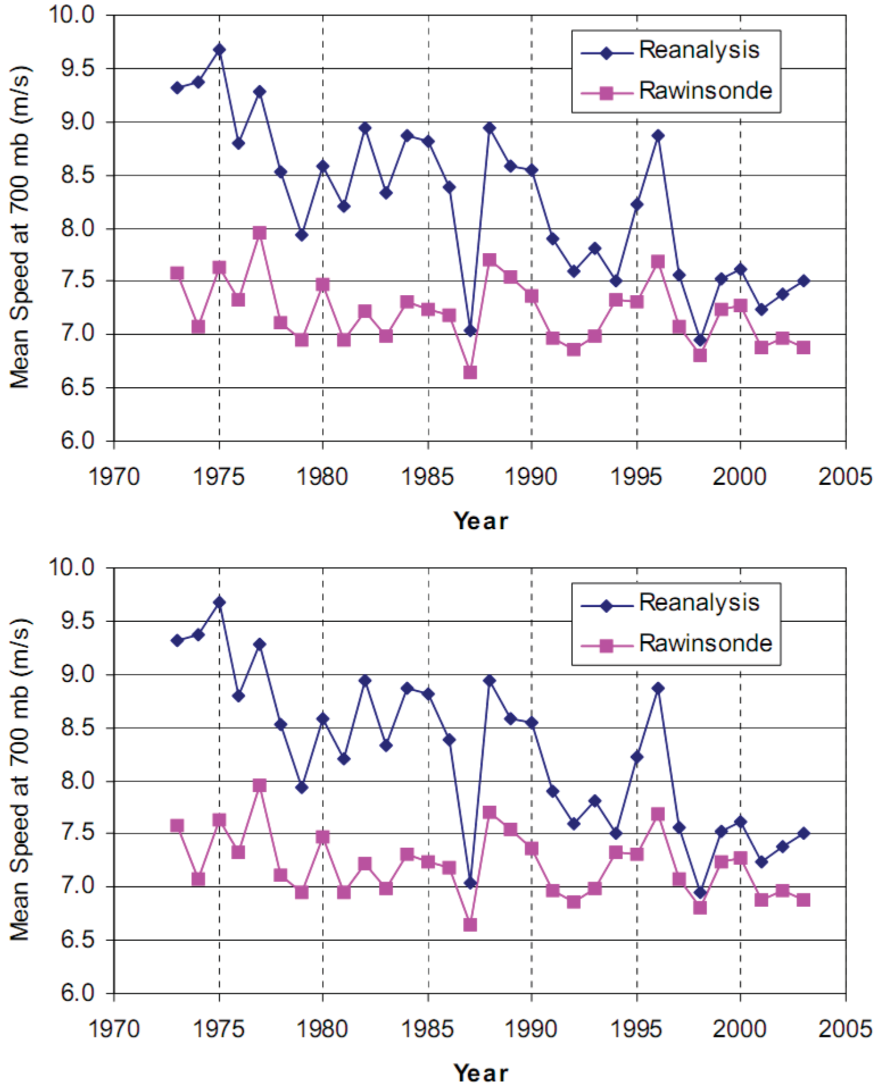

Figure 12-9 Comparison of mean annual speeds at 700 mb (3500 m above sea level) from reanalysis data (dark blue) and rawinsonde (magenta) observations over Denver, Colorado. [30]

[30] Brower, M. C., The Use of NCEP/NCAR Reanalysis Data in MCP (2006).

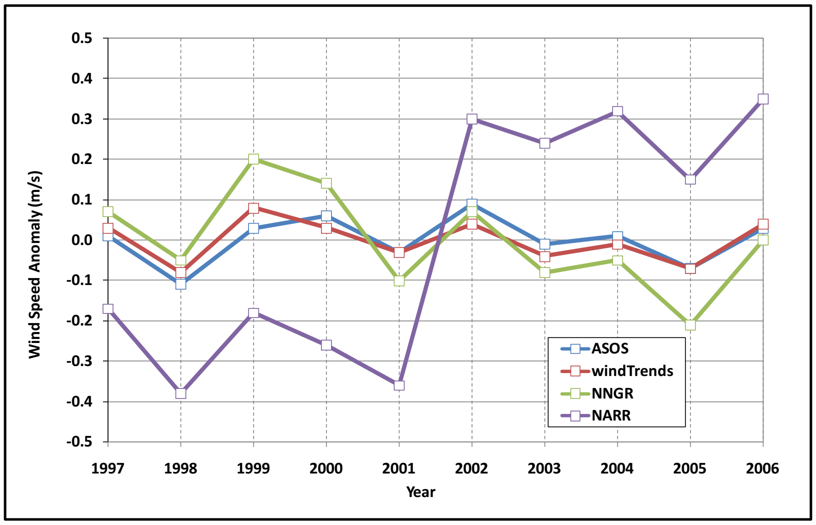

Figure 12-10 Average wind speeds for a subset of 185 ASOS stations from 1997 to 2006. The curves are drawn from ASOS data (blue), the NCEP/NCAR global reanalysis (NNGR) data set (green), the North American Regional Reanalysis (NARR) data set (purple), and the AWS Truepower "controlled reanalysis" data set (windTrends; red). (Source: AWS Truepower)

In response to these concerns, the concept of "controlled reanalysis" has been introduced. This approach is similar to reanalysis except that additional care is taken to employ data from a consistent set of observational systems and platforms (such as a fixed number of levels from a fixed set of rawinsonde stations). Research suggests that this method can reduce inconsistencies in traditional reanalysis. Still, whether the data produced in this fashion can be sufficiently homogeneous in regions where weather observations are of lower quality than in the United States is unknown.

In sum, modeled data sets can be useful compliments to surface and rawinsonde observations, but the resource analyst should be wary of relying on them entirely for MCP except when direct observations are unavailable or inadequate to the task. As always, the consistency of the modeled data should be verified through comparisons with independent data sources.

12.4. THE TARGET-REFERENCE RELATIONSHIP

Once the reference station (or stations) is selected, the next step is to establish a relationship between the reference winds and the target winds. This relationship is used to predict the long-term wind resource at the target site based on the entire valid (homogeneous) record of the reference station.

Many types of functional relationships can be used - too many to be described comprehensively here.[31] The most popular approaches are based on a linear transformation between the reference and target wind speeds

[31] Summaries of various methods can be found in Rogers, A. L. et al., Comparison of the Performance of Four Measure-Correlate-Predict Algorithms, Journal of Wind Energy and Industrial Aerodynamics (2005), and

(and, occasionally, directions). The general form of the linear equation is the familiar $y = mx + b$, where x is the reference wind speed, y is the target wind speed, m the slope, and b the intercept. If the "true" long-term mean wind speed at the reference station is known, then the predicted mean is given by the equation,

$$\bar{y} = m\bar{x} + b \qquad \textbf{Equation 12-4}$$

where the bar over the variable indicates an average. Usually, this equation is determined through a linear least-squares fitting procedure called a linear regression (see below).

A variety of non-linear methods (e.g., artificial neural networks or support vector machines) have also been proposed and studied, but they tend to be more complicated than linear methods and require more expertise. Only the linear methods will be discussed here.

Data Binning

One distinction between different linear methods is how the data are binned, or grouped in subsets. Unconstrained methods derive a single linear equation for all the data at once. Directional methods, which are also quite popular, construct a different linear equation for each of several direction bins. Matrix methods go further and bin the data by both direction and speed (and sometimes forego the full linear equation in favor of a ratio) [32]. Still other approaches bin the data by time of day (irrelevant when daily averages are used) or time of year.

The bulk method is the simplest to use and probably the most robust - meaning the least susceptible to error in inexperienced hands or under far-from-ideal conditions. Other methods require more time and experience. One complication of highly binned approaches is the need to deal with bins that have an insufficient number of counts to provide a reliable fit or ratio. Adjacent bins can be merged or a flexible bin size can be employed to overcome this difficulty.

Whether any particular approach produces a consistently more accurate estimate of the long-term mean wind resource is unclear, and depends at least in part on how the objective is defined. When it comes to a single parameter, the mean wind speed, one study employing eight different pairs of reference/target data sets found little difference between three linear methods - a bulk linear-regression method, a matrix-ratio method, and a variance-ratio method (described later). [33] Another study found a very slight reduction in

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Thoegersen, M. L., Measure-Correlate-Predict Methods: Case Studies and Software Implementation, European Wind Energy Conference (2007).

[32] Anderson, M. A Review of MCP Techniques (2004)

[33] Table 4 in Rogers (2005). A fourth method, which creates a separate linear equation for each component of the horizontal wind vector, performed poorly. Since this approach conflates wind direction and speed, it is not treated as a linear method here.

error when employing various directional and time-of-day binning approaches compared to a bulk linear-regression approach. [34]

When it comes to predicting the wind speed frequency distribution, however, the bulk linear-regression method does not perform as well. This issue is addressed below.

Fitting Methods

The simplest method of relating wind speed data from two towers is by taking the ratio of their means. (This is effectively a linear equation with $b = 0$.) The key problem with this approach is that it assumes a perfect correlation: increasing the reference wind speed by 10% produces a 10% increase in the target speed. If the correlation is actually much less than one, the result can be a substantial error in the predicted long-term mean wind speed, as too much weight is attached to the reference.

Binning approaches that employ ratios can get around this problem to some degree by allowing additional freedom in defining the target-reference relationship. This assumes that the bins span a wide range of wind speeds - directional binning alone may not be enough. A matrix method that bins by speed meets this test.

Alternatively, a linear equation can be established through a linear regression. All spreadsheet programs and some commercial wind resource analysis software contain routines to do this. The key thing to know about linear regressions is that they seek to minimize the sum of *squared* errors, meaning they are quite sensitive to large deviations between prediction and reality. As a result, just a few "outlying" points - such as may occur in wind data that has not been properly quality-controlled - can pull the fitted line significantly to one side. For this reason, professional statisticians often prefer other, more robust fitting methods; but for ordinary users, the simplicity and ease-of-use of the linear regression usually make it the method of choice.

Linear regression does not assume a perfect correlation. Indeed, when the correlation is weak, the slope tends to be small, so variations in the reference wind speed have little impact on the predicted target speed. Another advantage of linear regression is that it can easily incorporate more than one reference station at a time (a multiple linear regression). Sometimes different reference stations capture different aspects of the target site's wind climate - for example, a coastal station may be more representative of the target site than an inland station when the winds come from over the ocean, while the reverse is true when the winds originate from over land. The weight given to each reference station in the fit depends on that station's correlation with the target site and its statistical independence from other stations. A multiple linear regression can be a handy way of improving the correlation and allowing an objective determination of the

[34] Oliver, A; K. Zarling; "Time of Day Correlations for Improved Wind Speed Predictions", Renewable Energy Systems America Inc., www.res-americas.com/media/255156/time of day correlations for improved wind speed predictions - dr. andy oliver and kristofer zarling.pdf.

relative value of different stations. Nevertheless, if too many reference stations are used in a multiple linear regression, and especially if they are strongly correlated, there is a risk that the regression will be over-specified. This can produce poor results.

Predicting the Speed Distribution

A significant drawback of linear regression is that it tends to understate the degree of variation of the target wind speeds, especially when the correlation is weak. For a given linear equation $y = mx + b$, the variance - or standard deviation squared - of the target speeds is given by

$$\sigma_y^2 = m^2\sigma_x^2 \qquad \textbf{Equation 12-5}$$

The weaker the correlation, the smaller the slope, and therefore the smaller the variance of the predicted wind speeds. To accurately predict the speed distribution, in general, something more than a linear regression is required.

One simple but often effective approach is to scale the observed target site's wind speeds to the predicted long-term mean. Each speed value in the target data set is multiplied by the ratio of the predicted long-term mean to the observed mean:

$$v_i^{(pred)} = \frac{\overline{v}^{(pred)}}{\overline{v}^{(obs)}} v_i^{(obs)} \qquad \textbf{Equation 12-6}$$

This assumes, in effect, that the data measured at the site accurately capture the relative variation of the wind, so only the mean needs to be adjusted. In practice, this is usually a good assumption: rarely does the estimated power production vary by more than 1-2% simply due to variations in the speed distribution at the same tower, from one year to another, for the same mean year of measurements, the seasonal dependence of the speed distribution becomes a concern (as does the accuracy of the predicted mean speed). It is also not possible to reconstruct a time series of target data over the full period of reference data, if that should be desired, although that is usually not a serious drawback.

The variance-ratio method is another way of preserving the target site's variance. The idea is that the slope and intercept of the linear equation $y = mx + b$ are chosen to reproduce the observed variance and mean:

$$y = \frac{\sigma_y}{\sigma_x}x + \left(\overline{y} - \frac{\sigma_y}{\sigma_x}\overline{x}\right) \qquad \textbf{Equation 12-7}$$

The mean values (overbars) are from the concurrent target and reference data sets. The predicted long-term mean speed can be derived from this equation or from the linear-regression method. The latter is preferred, since only the linear regression considers the correlation in determining the size of the MCP adjustment; otherwise, the variance-ratio method effectively assumes perfect correlation.

Although the variance-ratio method will match the observed speed variance, there is no guarantee that it will produce the correct speed frequency distribution in detail, since the relationship between the target and reference speeds may (and usually does) vary with speed, direction, time of day, and other factors. Matrix-ratio methods can overcome this particular difficulty with appropriate binning; but even those methods break down when the correlation within each speed and direction bin is not very strong, i.e., when there is not a one-to-one correspondence between a particular reference speed and direction and the corresponding target speed and direction. This last shortcoming can be addressed by introducing random noise terms when reconstructing the target data set, but this can only provide an approximate solution.

Direction and Other Parameters

It is usually not necessary to use MCP to predict the target directional distribution, so long as there is at least a year of directional data from the target site. Where the on-site observations are inadequate, the simplest solution is to find the mean offset between the concurrent reference and target directions for each reference direction sector, and apply that offset to the full reference data record. This works well - as one might expect - when the directions are highly correlated, but it can break down in less ideal situations. A more general solution is to sample the directional distribution at the target for each reference direction. This method can readily be combined with the matrix sampling method described at the end of the previous section.

Other parameters, such as the observed temperature, can be adjusted to the historical norm using a linear regression between the reference and target site in the same manner as wind speed. If available, air pressure measurements can also be adjusted using this same method. The results can be used to adjust the estimated air density at the site.

Summary

While every method has its strong and weak points, it is generally best for the inexperienced analyst to stick with relatively simple, tried-and-true approaches. By this standard, it is hard to beat a bulk linear regression. It is easy to apply and its estimates of the long-term mean wind speed are about as accurate as any linear method. It is not suitable for predicting the speed distribution; for that, scaling the observed wind speeds to the predicted mean is recommended so long as there is at least nine months of valid on-site data. More complicated methods are best left to analysts with time and experience who can fully understand the potential benefits and pitfalls of applying them to the available data sample.

Section 13

13. WIND FLOW MODELING

The main purpose of wind flow modeling is to estimate the wind resource at every proposed or potential wind turbine location so that the wind plant's overall production can be calculated and its design can be optimized. This usually means extrapolating from the wind resource measured at one or more meteorological towers using a numerical wind flow model of some kind.

In an ideal world, wind flow modeling - just like shear and long-term climate adjustments - would not be necessary. Wind measurements would be taken at every likely turbine location to eliminate any possibility of significant error. For most projects this would be an expensive proposition, however. In practice, wind flow modeling is an essential part of the wind resource practitioner's toolkit. It is also one of the largest sources of uncertainty in most energy production estimates.

Aside from estimating the variation in the wind resource across the project area, wind flow modeling must account for each turbine's influence on the operation of other turbines - the so-called wake effect. Wake modeling is usually performed separately from wind flow modeling using specialized software. It is not discussed in this chapter.

Unlike most other chapters in this handbook, this chapter does not present a preferred model or modeling approach. There are simply too many methods with very diverse characteristics to take such a position. Instead, we content ourselves with providing an overview of the different modeling approaches that are available, including their strengths and weaknesses, and establish some general guidelines applicable to all methods - most important, the appropriate use of measurements to manage and limit errors.

Chapter 13 At-a-Glance

- There are a variety of spatial models that can be used to extrapolate the wind resource across a project site; each has its own strengths and weaknesses.
- The most common approach is to use a numerical flow model, of which there are several types based on different sets of physical equations. The types include linear flow models, non-linear flow models known as CFD models, and dynamic mesoscale atmospheric simulation models.
- WAsP is the most popular model currently in use. While suited for many situations, WAsP, a linear flow model, is not equipped to handle complex terrain, channeling through gaps, or temperature-driven wind patterns.
- Various CFD models have been gaining in popularity in recent years, and may provide useful insights in complex sites. They do not, as a rule, handle thermally stable conditions or thermally-driven circulations.
- Mesoscale numerical flow models solve the most complete set of physical equations, but they require a great deal of computing power, and most have not been adapted to the high spatial resolutions required for wind flow modeling.
- Inputs to numerical flow models include high-resolution topographical and land cover data, and measurements from a wind resource assessment measurement campaign.
- The uncertainty of the model can be estimated by comparing the projected wind speeds with the observed wind speeds for masts whose data are excluded as model inputs.

13.1. TYPES OF WIND FLOW MODELS

Spatial modeling approaches can be conveniently classed in four general categories: conceptual, experimental, statistical, and numerical.

Conceptual Models

Conceptual models are theories describing how the wind resource is likely to vary across the terrain. They are usually based on a combination of practical experience and a theoretical understanding of boundary layer meteorology.

A very simple conceptual model might state that the wind resource at one location (a turbine) is the same as that measured at a different location (a met mast). This could be a good model in relatively flat terrain or along a fairly uniform ridgeline, for example. Where the terrain and land cover vary substantially, a more nuanced picture is usually required. This might include theories concerning the influence of elevation on the mean wind speed, the relationship between upwind and downwind slope and topographic acceleration, channeling through a mountain gap, and the impact of trees and other vegetation. These concepts or theories are then turned into practical recommendations for the placement of wind turbines, accompanied by estimates of the wind resource they are likely to experience.

As wind projects become larger and are built in ever more varied wind climates, it becomes more and more difficult to implement a purely conceptual approach in a rigorous or repeatable way. Nevertheless, a good conceptual understanding of the wind resource is a valuable asset in all spatial modeling. Most important, it provides a check on the reasonableness of other methods. A good conceptual understanding is better than a bad numerical model, or a good numerical model that is wrongly applied.

Experimental Models

Experimental methods in this context refer mainly to creating a sculpted scale model of a wind project area (such as that shown in Figure 13-1) and testing it in a wind tunnel. (This is also known as physical modeling, a term we avoid because of possible confusion with numerical wind flow models, which are based on physical principles.) The conditions in the wind tunnel - such as the speed and turbulence – must be matched to the scale of the model to replicate real conditions as closely as possible. While the wind tunnel is

Figure 13-1 Scale model of Altamont Pass used in wind tunnel tests. (Source: Lubitz, W.D. and R.B White, "Prediction of Wind Power Production Using Wind-Tunnel Data, a Component of a Wind Power Forecasting System" (Proceedings of AWEA WindPower 2004)

running, the wind speeds are measured at various points on the scale model using tiny anemometers (usually hot-wire anemometers). The results form a picture of how the wind varies across the site. The relative speeds between points are then usually related to a mast where the speeds have been measured in the field.

Although studies comparing experimental methods to other methods are scarce, there is no reason to think this type of approach cannot work well under many conditions. It may even provide unique insights in areas where numerical wind flow models are prone to break down, such as near the edge of a steep cliff. Still, few wind resource analysts adopt this method because of the time and special skills required to build an appropriate model and the need for access to a wind tunnel. In addition, the method has some limitations (such as the difficulty of modeling thermally stable conditions, and the challenge of appropriately matching atmospheric parameters to the physical scale).

Statistical Models

Statistical models are based on relationships derived entirely or primarily from on-site wind measurements. Typically one tests different predictive parameters - such as elevation, slope, exposure, surface roughness, and other indicators - to find those that appear to have the strongest relationship with the observed wind resource at several masts. In principle, any parameters can be used, although in practice it makes sense to focus on those for which there is a reasonable theoretical basis for believing a relationship should exist. This is one place where a good conceptual understanding is valuable.

It is probably easiest to explain this approach by example. Suppose one has measured the mean wind speeds at several different towers at different points within a wind resource area. Suppose the speeds are plotted against, say, elevation, and a strong correlation is found. From this relationship a linear equation ($y = mx + b$) could be derived, and then applied to predict the speed at any other point in the area.

Statistical models are appealing because they are well grounded in measurement and are fairly simple and transparent - unlike numerical wind flow models, which often seem more like "black boxes." They can work surprisingly well, particularly for wind climates driven by synoptic-scale winds (i.e., where thermally driven mesoscale circulations are largely absent), which tend to exhibit the clearest relationships between wind speed and certain topographic indicators such as elevation and exposure. Figure 13-2 illustrates the relationship observed at 74 towers in seven wind resource areas between variations in wind speed and downwind exposure, defined as the difference between the elevation of a given point and the average elevation out to 3000 m in the downwind direction.

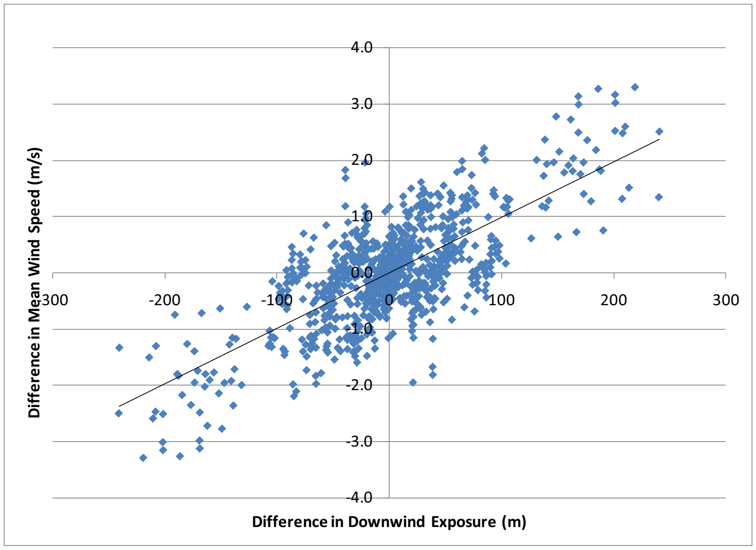

Figure 13-2 Data from pairs of 74 towers in seven wind resource areas indicate a significant relationship between the differences in mean speed and downwind exposure. Such a statistical relationship can be used to predict variations in wind speed across a project area. (Source: AWS Truepower)

One of the potential limitations of statistical methods is that they can produce large errors when making predictions outside the range of conditions used to train the model. Suppose, for example, that one has data from three towers at varying elevations along a ridge top. Will the relationship between mean speed and, say, elevation implied by these three towers hold when predicting the speed off the ridge top? Not necessarily, because the topographic influence on the wind flow may be very different at the top compared to the slopes. In this respect, statistical models can be less reliable than numerical wind flow models, which are designed to produce plausible (if not accurate) results in a wide range of conditions.

Determining the accuracy of a statistical model is a particular challenge of this approach. To derive an objective estimate of the uncertainty, it is necessary to divide the dataset into two groups: one to train the model, the other to validate the model. The most rigorous procedure is to derive empirical relationships by fitting variables and functions to the "training" data and then determine the error with respect to the "validation" data that have been withheld. Many sites lack sufficient data with which to conduct such a validation. In such cases where the validation data must be included in the training data set, there is a tendency to underestimate the errors.

Nevertheless, statistical models are a valid approach when proper procedures are followed. Statistical methods can also be combined with other approaches, such as numerical wind flow models. A good example of this is the Ruggedness Index (RIX) correction that is sometimes used with the WAsP model (described below). RIX is a parameter that has been found through statistical modeling to be a good predictor of WAsP errors in some circumstances.

Numerical Wind Flow Models

The most popular methods of spatial modeling rely mainly on numerical wind flow models. There are several wind flow models in use by the wind industry today, which are based on a variety of theoretical approaches. All attempt to solve at least some of the physical equations governing motions of the atmosphere, with varying degrees of complexity. The models fall into four general categories: mass-consistent, Jackson-Hunt, computational fluid dynamics (CFD), and mesoscale numerical weather prediction (NWP) models.

Mass-Consistent Models. The first generation of wind flow models developed in the 1970s and 1980s (e.g., NOABL 35, MINERVE) were mass-consistent models, so called because they solve just one of the physical equations of motion, that governing mass conservation. When applied to the atmosphere (assuming it is incompressible, a good assumption within the boundary layer), the principle of mass conservation implies that wind forced over higher terrain must accelerate so that the same volume of air passes through the region in a given time. As a result, these models predict stronger winds on hill and ridge tops and weaker winds in valleys. They cannot handle thermally-driven wind patterns, such as sea breezes and mountain-valley circulations, and flow separations on the lee side of hills or mountains.

The solution offered by a mass-conserving model is not unique: the governing equation actually permits an infinite variety of solutions. Instead, most models are designed to depart by the smallest possible amount from an initial wind field "guess" derived from observations. Such a characteristic sets this type of model somewhat apart from other numerical models, which make no such assumption. It also means that mass-consistent models are able to take advantage of data from additional meteorological towers in a natural way, by modifying the initial guess.

Jackson-Hunt Models. The next generation of models (e.g., WAsP [36, 37], MS-Micro or MS3DJH [38, 39],Raptor [40], Raptor NL [41]) were originally developed in the 1980s and 1990s based on a theory

[35] Phillips, G. T, "A preliminary user's guide for the NOABL objective analysis code". Report from Science Applications, Inc., La Jolla, California, 115 pp. (1979).

[36] Troen, I; Petersen, E.L, "European Wind Atlas". Report from the Risoe National Laboratory, Roskilde, Denmark. (1989).

[37] Troen, I, "A High Resolution Spectral Model for Flow in Complex Terrain". Proceedings from the 9th Symposium on Turbulence and Diffusion, Roskilde, Denmark. (1990).

[38] Beljaars, A.C.M.; Walmsley, J.L; Taylor, P.A., "A Mixed Spectral Finite-Difference Model for Neutrally Stratified Boundary-Layer Flow over Roughness Changes and Topography". Boundary-Layer Meteorol., vol. 38, pp. 273-303. (1987).

[39] Taylor, P.A.; Walmsley, J.L; Salmon, J.R, "A Simple Model of Neutrally Stratified Boundary-Layer Flow over Real Terrain Incorporating Wave Number-Dependent Scaling". Boundary-Layer Meteorol., vol. 26, pp. 169-189. (1983).

[40] Ayotte, K.W; Taylor, P.A., "A Mixed Spectral Finite-Difference 3D Model of Neutral Planetary Boundary-Layer Flow over Topography. J. Atmos. Sci., vol. 52, pp. 3523-3537. (1995).

[41] Ayotte, K.W, "A nonlinear wind flow model for wind energy resource assessment in steep terrain". Proceedings of Global WindPower Conference, Paris, France. (2002).

advanced by Jackson and Hunt.[42] They go beyond mass conservation to include momentum conservation by solving a linearized form of the Navier-Stokes equations governing fluid flow. The most important simplification in the Jackson-Hunt theory is that the terrain causes a small perturbation to an otherwise constant background wind. This assumption allows the equations to be solved using a very fast numerical technique.

No spatial modeling chapter would be complete without a discussion of WAsP (shown in Figure 13-3), a Jackson-Hunt model developed by the Risoe National Laboratory of Denmark, which has been and probably remains the most widely used numerical wind flow model in the wind industry. The "WAsP method" (see Figure 13-4) is deeply entrenched in spatial modeling practice, especially in Europe. It proceeds in two stages: (a) The observed wind at a mast is used to derive the background wind field, which represents the wind resource that would exist in the absence of terrain. This background wind field is typically summarized in a file known as a wind atlas or library file. (b) The process is subsequently reversed using the background wind as input to predict the wind profile at other points.

[42] Jackson, P.S; Hunt, J.C.R., "Turbulent Wind Flow over Low Hill"Quart. J. R. Met. Soc., vol. 101, pp. 929-955. (1975).

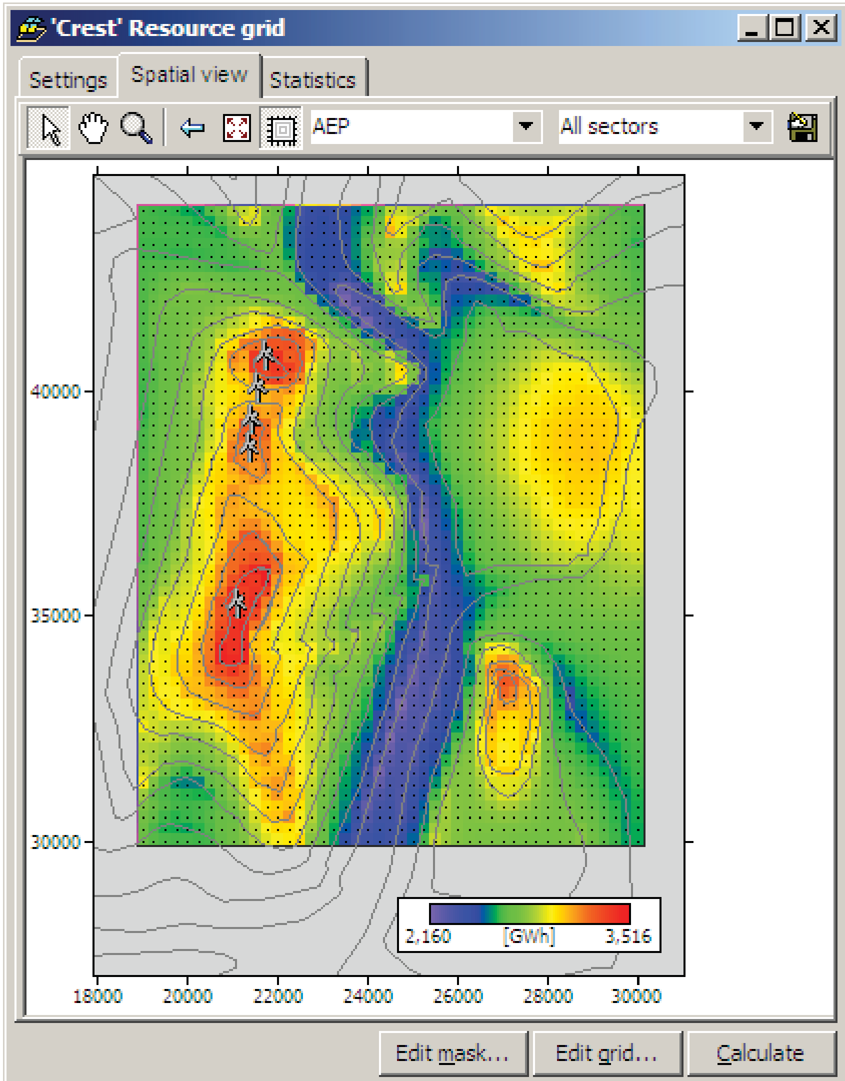

Figure 13-3 WAsP, depicted here, is a popular wind flow modeling application. Like other Jackson-Hunt models as well as mass-consistent models, WAsP captures the tendency of wind speed to increase over high ground and decrease in valleys. Ridges oriented perpendicular to the flow exhibit the greatest topographic acceleration. (Source: WAsP).

In addition to implementing the basic Jackson-Hunt approach, WAsP contains several modules that address various needs in wind flow modeling, including the ability to incorporate the effects of surface roughness changes and obstacles. Perhaps because WAsP was developed in the relatively flat terrain of northern Europe where roughness changes and obstacles are among the main factors influencing the wind resource, these modules have been developed to quite an advanced degree.

It is widely recognized that WAsP – along with other Jackson-Hunt models – is not equipped to handle complex terrain. "Complex" in this context is usually defined as terrain where the slope exceeds 30% over a significant portion of the area. The essential problem is that steep terrain induces changes in the wind flow that do not satisfy the assumption of a small perturbation. The overlooked effects may include recirculation behind cliffs, flow separations at abrupt changes in slope, and vertical winds.

The WAsP model also ignores effects of thermal stability and temperature gradients. Thermal stratification and buoyancy forces can have a large influence on the response of wind to terrain. When the boundary layer is thermally stable, the air near the surface is cooler and denser than the air aloft. The wind therefore resists going over higher terrain, and instead seeks a path around it, through channels or gaps, or is blocked. Indeed, when WAsP was first applied in coastal mountain passes where the first U.S. wind farms were built, it failed to predict the wind resource distribution accurately. This experience gave wind flow modeling something of a bad name in U.S. wind resource assessment circles.

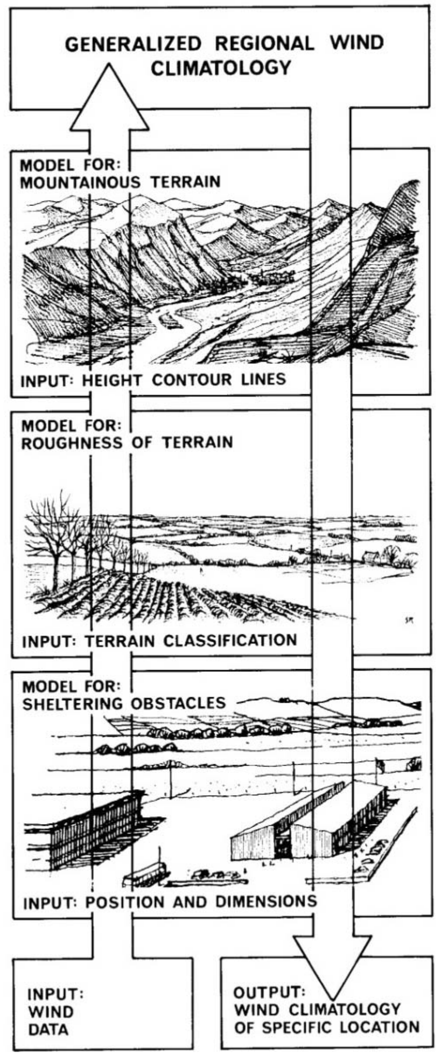

Figure 13-4 The WAsP mapping process. (Source: WAsP)

Despite its known limitations, WAsP remains very popular. This is partly because many wind project sites do not involve very steep terrain or significant mesoscale circulations. In addition, practical steps can be taken to improve the results. One method is to install additional masts so as to limit the distance over which the model must extrapolate the resource. Also, in some instances, it has been shown that errors can be reduced through the RIX adjustment. The RIX parameter represents the proportion of terrain upwind of a point exceeding a certain slope threshold, such as 30%. Relative wind speeds between two points are adjusted according to a simple formula that depends on the difference in RIX between them. Experiments have shown that this adjustment can be quite effective.

Finally, more sophisticated models (described below) are sometimes no more accurate than first-or second-generation wind flow models. This last point reflects a hard truth of atmospheric modeling: it is exceptionally difficult to do it well, and sometimes it is better to ignore aspects of wind flow one cannot simulate well than to simulate them poorly.

CFD Models. As personal computers have grown more powerful, it is natural that CFD models – computer programs designed originally to model turbulent fluid flows for airplane bodies, jet engines, and the like – would be turned to the task of spatial wind resource modeling.

The critical difference between CFD and Jackson-Hunt models is that CFD models solve a more complete form of the equations of motion known as the Reynolds-averaged Navier-Stokes, or RANS, equations. They do not assume the terrain induces a small perturbation on a constant wind field. This means they are capable of simulating non-linear responses of the wind to steep terrain, such as flow separation and recirculation (Figure 13-5). They also do not have to make certain other simplifying assumptions, such as that shear stress and turbulence act only near the surface. This, in turn, allows CFD models to simulate the influences of roughness changes and obstacles directly. (WAsP and other linear flow models, in contrast, generally do this in separate modules.)

Although CFD models have not always proven to be a significant improvement over other modeling techniques, they nonetheless represent an important new tool in the resource analyst's toolkit. Among their advantages are that they provide an independent picture of the wind resource that often looks quite different from that generated by Jackson-Hunt models like WAsP; and they can provide useful information concerning turbulence intensities, shear, direction shifts, and other features of wind flow in complex terrain.

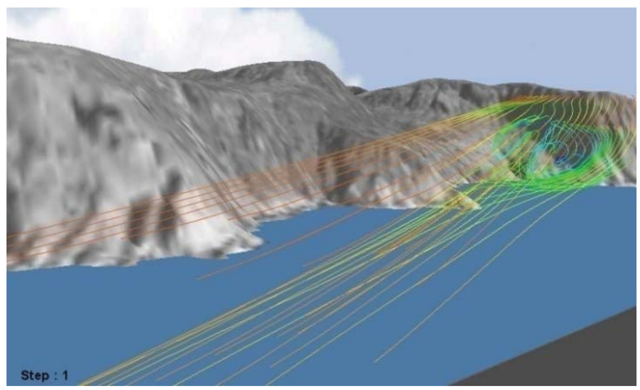

Figure 13-5 CFD models like WindSim, depicted here, are capable of simulating non-linear flow features as recirculation behind steep terrain. (Source: WindSim)

Some CFD models have shown very good agreement to wind tunnel experiments for 2D and 3D flows around idealized escarpments and steep hills, even on the lee side with the recirculation zone.[43, 44] At the same time, validation tests of CFD models in real conditions have sometimes proved disappointing. The Bolund experiment undertaken by the Risoe Lab (Denmark) involving more than 35 different CFD models showed that "the average overall error in predicted mean velocity of the top ten models (all RANS-based) was on the order of 13-17% for principal wind directions." [45]

[43] Bitsuamlak, G. T; Stathopoulos, T; Bédard, C., "Numerical Evaluation of Wind Flow over Complex Terrain: Review". J. Aerosp. Engrg. vol. 17,, pp. 135-145. (2004).
[44] Murakami, S; Mochida, A; Kato, S., "Development of local area wind prediction system for selecting suitable site for windmill". J. Wind Eng. Ind. Aerodyn., vol. 91, pp. 1759-1775. (2003).
[45] Sumner, J., C.; Watters, S; Masson, C., "CFD in wind energy: the virtual, multiscale wind tunnel". Energies, vol. 3, pp. 989-1013. (2010).

Clearly, the success of CFD modeling is not assured, and there is a continuing need to validate CFD results with high-quality wind measurements. Problems have been ascribed to various factors, including inaccuracies in initial and boundary conditions (which are usually assumed to be homogeneous and follow a neutrally stratified, logarithmic profile), limited grid resolution, and treatment of turbulence. The added complexity of the models may be a problem as some users may not be well equipped to run them properly. Another factor is that CFD models are not designed to take into account any circulations due to temperature gradients. The lack of a complete prognostic equation for temperature in CFD models is, in turn, the result of another assumption made in most CFD models, which is that the wind flow is steady-state. In a manner not unlike WAsP, CFD models assume a constant incoming wind field.

Mesoscale Numerical Weather Prediction Models. The last class of wind flow models covered in this chapter is the mesoscale NWP model. This type of model has been developed primarily for weather forecasting. Like CFD models, mesoscale models solve the Navier-Stokes equations. Unlike CFD models, however, they include parameterization schemes for solar and infrared radiation, cloud microphysics and convection (cumulus clouds), a soil model, and more. Thus, they incorporate the dimensions of both energy and time, and are capable of simulating such phenomena as thermally driven mesoscale circulations (such as sea breezes) and atmospheric stability, or buoyancy. In the world of mesoscale modeling - as in the real world - the wind is never in equilibrium with the terrain because of the constant flow of energy into and out of the region, through solar radiation, radiative cooling, evaporation and precipitation, the cascade of turbulent kinetic energy down to the smallest scales and dissipation into heat - even sound waves.

Mesoscale models consequently offer considerable hope for simulating wind flows accurately in complex terrain. They have, however, one big drawback: they require enormous computing power to run at the scales required for the assessment of wind projects. The typical model resolution for most mesoscale simulations is on the order of kilometers - meaning a single grid cell is kilometers across. It is clearly impossible to obtain a detailed picture of the wind resource within a project area at such a scale.

One way around this problem is to couple mesoscale models with a microscale model of some kind. This could be a statistical model, if there is sufficient on-site wind data to create reliable statistical relationships. More often, it is a simplified wind flow model - usually either a mass-consistent model or a Jackson-Hunt model. Examples include AWS Truepower's MesoMap [46] and SiteWind systems, 3Tier's FullView system,

[46] Brower, M., "Validation of the WindMap Program and Development of MesoMap". Proceeding from AWEA's WindPower conference. Washington, DC, USA. (1999).

the Risoe National Laboratory's KAMM-WAsP system [47], and Environment Canada's AnemoScope system [48].

Research suggests, not surprisingly, that such methods can be more accurate than simplified wind flow models where mesoscale effects play a significant role. One example is the wind resource in a coastal mountain pass such as Altamont Pass in California. Here a model such as WAsP predicts that the best winds should be at the top of the pass, whereas a mesoscale-microscale modeling approach like SiteWind predicts the acceleration of the relatively cool and dense marine air mass as it flows down the slope (Figure 13-6). The result is a definite improvement in accuracy.

[47] Frank, H.P., O. Rathmann, N. Mortensen, and L. Landberg "The Numerical Wind Atlas, the KAMM/WAsP Method". Riso-R-1252 report from the Risoe National Laboratory, Roskilde, Denmark. 59 pp. (2001).

[48] Yu, W., R. Benoit, C. Girard, A. Glazer, D. Lemarquis, J.R. Salmon, and J.-P. Pinard " Wind Energy Simulation Toolkit (WEST): a Wind Mapping System for Use by the Wind-Energy Industry ". Wind Eng., vol. 30, pp. 15-33. (2006).

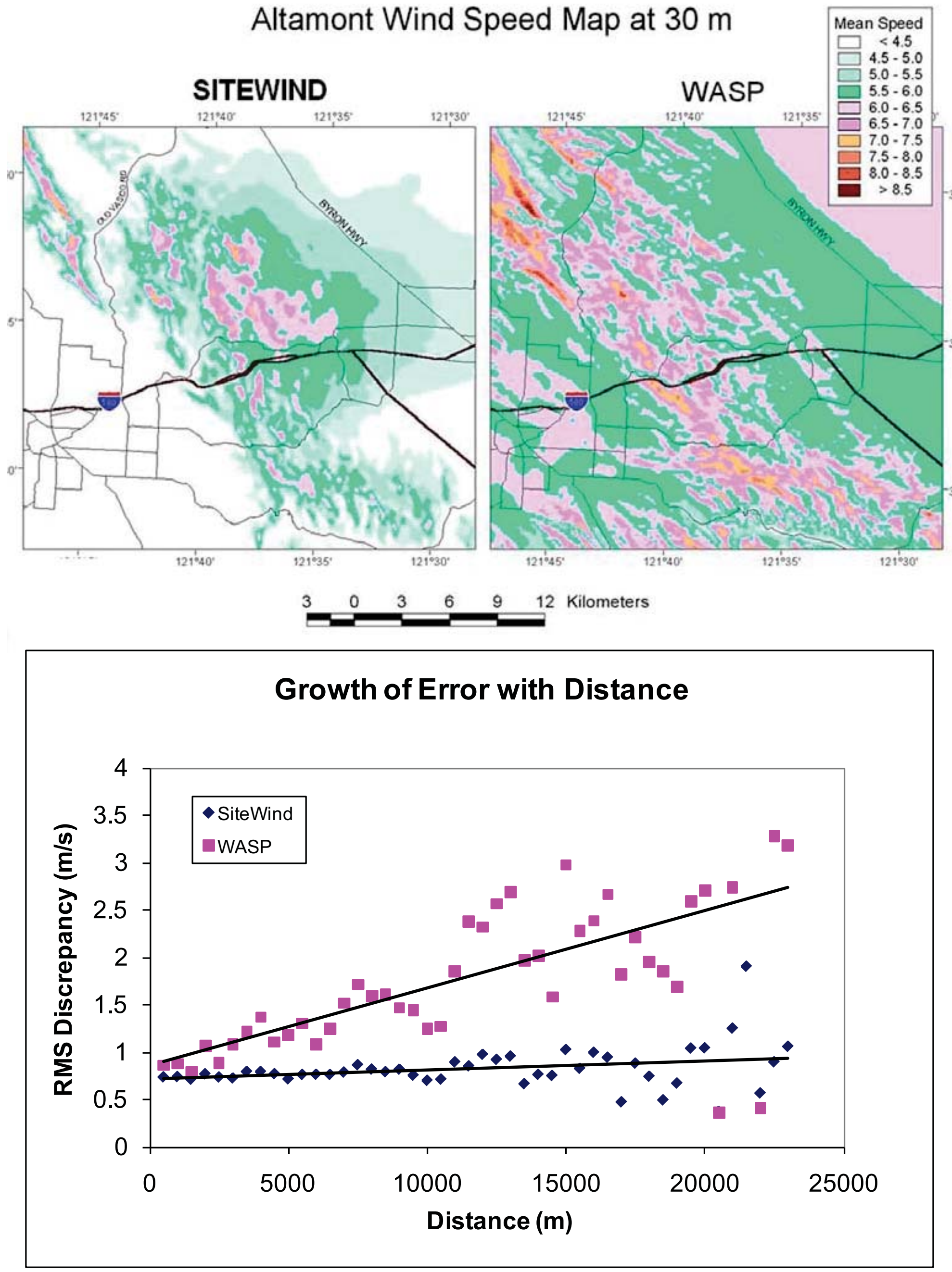

Figure 13-6 ***Top*****: Wind resource maps created by the SiteWind mesoscale-microscale modeling (top, left) system and by WAsP (top, right). The SiteWind map shows the wind resource concentrated on the eastern slopes approaching Byron Highway, the result of gravity acting on relatively cool, dense marine air. WAsP suggests the wind resource is more widely distributed and is at a maximum at the top of the pass.** ***Bottom*****: Comparison with observations indicates the SiteWind analysis is more correct. [49])**

[49] Reed, R; Brower, M; Kreiselman, J., "Comparing SiteWind with standard models for energy output estimation". Proceedings from EWEC, London, UK. (2004).

Altamont Pass represents a severe test for other models because the masts span a large distance - nearly 25 km - and mesoscale circulations are the key factor determining the distribution of the wind resource. In project areas dominated by synoptic-scale winds, on the other hand, the advantages are less decisive, and they are likely to diminish further or disappear at short distances from observational masts. Below the effective scale of the mesoscale model - say, a few hundred meters to a few kilometers - the microscale model dominates, and no improvement over conventional modeling is possible.

Ultimately it would be desirable to adapt a mesoscale model to run directly at the resolution required for wind plant micrositing (e.g., 50 m), thus eliminating the need for a simplified downscaling approach. In this mode, and with appropriate modifications, they begin to operate like large-eddy simulation models, which are used to simulate non-steady flows at very high resolution (meters). This approach is becoming feasible with large distributed computing networks. Still, the potential improvement in accuracy relative to the computer cost has not been evaluated. If successful, such an approach will most likely be reserved for the largest and most complex wind project areas, where the additional cost can be justified.

13.2. APPLICATION OF WIND FLOW MODELS

With such a wide variety of options for spatial modeling, it is clear that no single approach can be recommended above all others and in every circumstance. To narrow the discussion a little, we will focus on numerical wind flow models, which are by far the most widely used. The following guidelines are applicable to such models.

Topographic Data

Accurate, high-resolution topographic data is essential for all wind flow modeling. A typical spatial resolution for modeling is 50 m. (Often the data are resampled to this scale from a higher resolution.) Resolutions as high as 10 m or 30 m are sometimes used, but it is unclear that they confer much benefit in overall accuracy, since turbine rotors are typically 70 to 100 m in diameter, and turbines effectively average the wind resource over this area.

In the United States, the preferred source of topographic data is the U.S. Geological Survey (USGS) National Elevation Dataset (NED), with a spatial resolution of 10 m or 30 m (except in Alaska, where the resolution is 60 m). Outside the United States, data of similar quality may be available from national mapping agencies, or analysts may use the Shuttle Radar Topographic Mission data set, with a resolution of 90 m.

Land Cover Data

It is likewise important to employ accurate, high-resolution land cover data. Most modern land cover data sets are created from satellite imagery, like that produced by the Landsat and Satellite Pour l'Observation de la Terre (SPOT) satellites. Since the land cover classifications are derived by computer software from spectral measurements and have only been checked in certain areas, they are subject to error. Their accuracy should be verified, where possible, through aerial and ground photographs.

In the United States, the preferred data set is the National Land Cover Database (NLCD 2001), a 30-m resolution data set derived from Landsat Thematic Mapper imagery. A similar data set known as EarthSat GeoCover is available for purchase in other regions of the world from MDA Federal, Inc. Many countries have home-grown land cover data sets, and Europe is covered by the Coordination for Information on the Environment (CORINE) system.

In most cases, the land cover classifications must be converted to roughness values (in meters) to be used in numerical wind flow modeling. There is no universally accepted roughness conversion system. The following table presents a range of values used by AWS Truepower.

Land Cover Type	Roughness Range (m)
Water	0.001
Urban/Developed Area	0.3 – 0.75
Forest	0.9 – 1.125
Wetland	0.15 – 0.66
Shrubland	0.1 – 0.2
Cropland	0.03 – 0.07

Table 13-1 Roughness ranges for typical land use/land cover categories. Values may vary with geographic location. (Source: AWS Truepower)

For more precise land cover information, some private companies (e.g. Intermap Technologies) offer high-resolution surface models that include features such as buildings, vegetation and roads, in addition to terrain elevation data.

<u>Mast Number and Placement</u>

To achieve the standards of accuracy required for energy production estimates for utility-scale wind projects, all wind flow modeling must be anchored in high-quality observations from the project area. A minimum of one mast, equipped and installed to the specifications described in this handbook, is recommended, although a remote sensing system may serve as the primary observational platform in some cases.

Wind resource data should be collected at locations representing the full range of wind conditions likely to be encountered by the wind turbines in the project. Where this criterion is not met, the uncertainty in the spatial modeling increases substantially. This criterion is sometimes translated into distance - as in the rule that no turbine should be placed farther than one kilometer from a met mast in complex terrain. Still, distance is only one factor to consider; differences in elevation, topographic exposure, slope, and aspect (angle of slope with respect to north) may also be important.

In general, the greater the number of masts deployed, the smaller the uncertainty in the predicted resource. As a rough rule, the uncertainty varies as the inverse of the square root of the number of masts:

$$\frac{1}{N} \qquad \textbf{Equation 13-1}$$

This rule applies only if the masts are well distributed throughout the proposed turbine array, however. If the masts are clumped in one area, while the turbines are in a different area, then the additional masts provide little, if any, benefit. Examples of preferred and poor mast placement are provided in Figure 13-7.

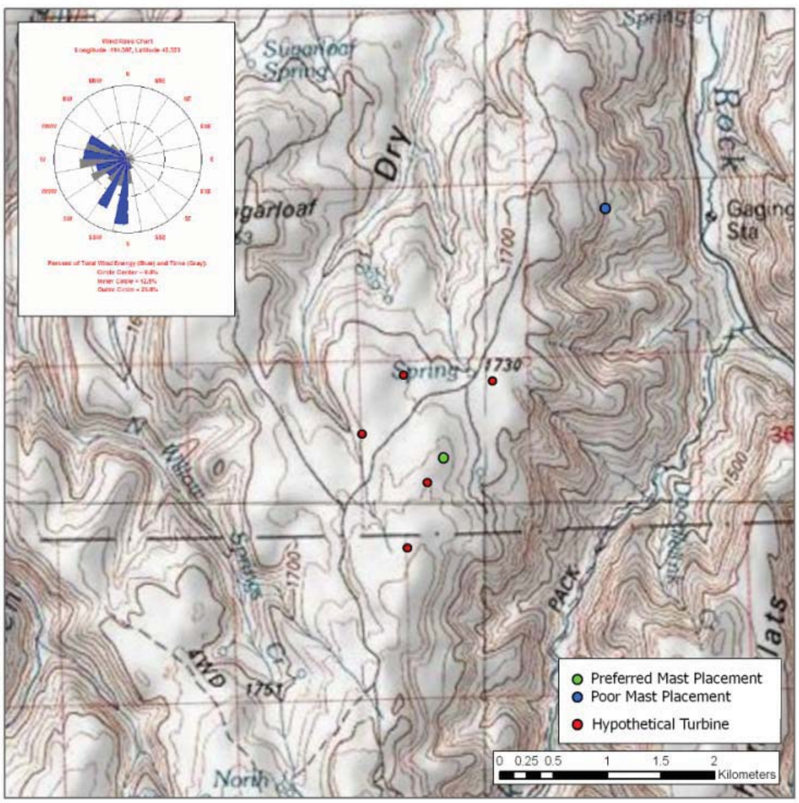

Figure 13-7 Examples of preferred and poor mast placement for a hypothetical turbine layout. The preferred mast location is within the turbine array. (Source: AWS Truepower)

Adjustments to Multiple Masts

Most numerical wind flow models are equipped to use data from just one mast. These days, however, wind projects usually employ several masts. This raises the question of how to make the best use of the additional data.

One approach (often used for WAsP modeling) is to divide the project area into sections, each of which is assigned to one mast. The sections may be defined by distance (i.e., the closest mast is assumed to "dominate" the area), or they may be defined by some other criterion, such as topographic similarity (e.g., ridge-top sections are assigned to ridge-top masts). The simulation for each mast is done separately from the others, and the wind resource predictions for the turbines within a section are drawn from the mast that section is assigned.

This approach is pragmatic, but it can be awkward when - as often happens - there is a discontinuity in the predicted wind resource where two sections meet. The resulting energy production estimate may change unrealistically if a turbine is moved from one side of the dividing line to the other.

A more esthetically pleasing - if not more accurate - approach is to smoothly blend the results for the different sections. A relatively simple blending technique is to assign a weight to the wind resource prediction from each mast proportional to the inverse of the squared distance to that mast:

$$\overline{v} = \frac{\sum \frac{v_i}{d_i^2 + C}}{\sum \frac{1}{d_i^2 + C}} \qquad \textbf{Equation 13-2}$$

Here, v_i is the speed predicted from mast i, d_i is the distance from that mast to the point in question, and C is a smoothing constant that prevents the equation from becoming undefined very close to a mast. Since most wind flow models do not perform this blending, it may be necessary to write software to do it.

Distance-weighted blending rests on the assumption that the uncertainty associated with the prediction from any given mast depends most importantly on the distance to that mast. As noted, however, distance is only one consideration. The modeling uncertainty - and therefore the blending weight - also depends on the similarity of topographic and other conditions between a given point and each mast. If the point is on a ridge top, it would be reasonable to give a ridge-top mast more weight in the adjustment than a mast far down the slope, even if the latter is closer. Although an approach based on topographic similarity and other factors is more defensible, it is also more difficult to put into practice, as it requires an understanding of how uncertainty varies with these factors. Thus, most resource analysts rely on a distance-squared blending alone.

13.3. DETERMINING THE MODELING UNCERTAINTY

Given the complexities of numerical wind flow modeling, it is important to develop a clear understanding of the uncertainty in the results. It is possible to directly estimate the modeling uncertainty if the following criteria are met:

- There are at least five masts in the project area.
- The masts are well distributed within the proposed turbine array and among the site conditions likely to be experienced by the wind turbines.
- There is sufficient data from each mast to accurately compare mean annual wind speeds.

Assuming these conditions are met, then the process is straightforward. First, one of the masts is designated as the target mast. Next, the data from the other masts are combined with the wind flow model to predict the wind resource at the target mast using the same blending method that is employed for the final wind mapping. Then, the error between the predicted and observed mean wind speed is calculated. After the process is repeated for each mast, the standard deviation of the errors, or standard error, can be calculated.

If there is insufficient data to produce a reliable result, then the resource analyst must rely on experience from other sites. An assessment of the complexity of the terrain, variations in land cover, and the possible role of coastal sea breezes and other mesoscale circulations, comes into play here.

Depending on the situation and model, errors typically range from around 3% of mean speed in simple, open terrain, to 15% in complex terrain or where there is significant channeling, coastal effects, or other factors at play.

Section 14

14. UNCERTAINTY IN WIND RESOURCE ASSESSMENT

Wind resource estimates are useful only if their uncertainty is well defined. Unless the resource analyst can offer a degree of confidence that the wind resource falls within a specified range, it is not possible to construct a sound financial model for a wind project investment.

The uncertainty present in all wind resource estimates is primarily related to the following factors: wind speed measurements, the historical climate adjustment, potential future climate deviations, wind shear, and the spatial wind resource distribution. This chapter reviews these factors and provides a range of estimates for each. Except where otherwise noted, the uncertainty estimates are expressed as a percent of the speed and represent one standard error of a normal distribution.

Not addressed in this chapter is the relationship between the uncertainty in speed and the uncertainty in energy production, which varies depending on the turbine model, speed frequency distribution, and other factors. The uncertainty in turbine performance and losses is also not considered. These topics, along with other elements of energy production estimation, are outside the scope of this handbook.

Chapter 14 at a Glance

- Wind resource estimates should be accompanied by an estimate of the uncertainty, or margin of error.
- The uncertainty typically has several components, including the measurement, shear, historical climate correction, future climate variability, and wind flow modeling uncertainties.
- The measurement uncertainty represents the accuracy of the estimated free-stream wind speed based on the anemometer data.
- The historical wind resource uncertainty reflects the uncertainty in the climate-correction process, including correlation, reference inhomogeneities, and the potential for climate change.
- The normal variability in the wind resource over the life of the plant, as well as the possible effects of climate change, is accounted for in the climate variability uncertainty.
- The wind shear uncertainty captures the uncertainty associated with the shear calculation as well as the possible change in shear above the mast height.
- The wind flow modeling uncertainty can vary greatly depending on the complexity and size of the project area, the model used, the number and placement of masts, and other factors.

14.1. MEASUREMENT UNCERTAINTY

This is the uncertainty in the free-stream wind speed as measured by the anemometers after data validation and adjustments. It reflects not just the uncertainty in the sensitivity of the instruments when operating under ideal, wind-tunnel conditions but also their performance in the field, where they may be subject to turbulent and off-horizontal winds; the possible effects of the tower on the observed speeds; and problems such as icing that may be missed in the validation. There may be additional uncertainties associated with specific anemometers and anemometer types, such as those resulting from manufacturing flaws or damage incurred in the field.

The uncertainty associated with anemometer response under ideal conditions (called the sensor response uncertainty) is typically estimated to be 1.0%-1.5% for a single anemometer. Considering that they are used for power curve testing and thus represent the de facto standard for estimating turbine output, Class I sensors may be assumed to have a somewhat lower uncertainty than other sensors. The other components of the measurement accuracy vary greatly depending on the circumstances. A typical range of estimates for a single anemometer mounted in accordance with the guidelines presented in this handbook, and whose data are subjected to high-quality validation procedures, is 1.3%-2.5%.

The measurement accuracy can be considerably improved by averaging the data from two sensors mounted in different directions at the same height on the mast. For those direction sectors where neither sensor is in the direct shadow of the tower, it is reasonable to reduce the uncertainty by the square root of two (1.414). When appropriate mounting guidelines and validation protocols are observed, the resulting combined uncertainty range is 0.9%-1.8%. Some judgment must be applied, however, since there is no benefit to averaging when there are significant biases affecting both sensors to a similar degree - for example, the impacts of turbulence and upflow angle. Where these effects are judged to be small, the full reduction can be applied, but where it is suspected they are substantial, it is safer to take no credit for averaging in the overall uncertainty.

14.2. HISTORICAL WIND RESOURCE

This uncertainty addresses how well the site data (after adjustment via MCP) may represent the historical norm. It is related to the interannual variability of the wind climate and the correlation of the site data with the long-term reference. Referring again to the equation from chapter 12:

$$\cong \sqrt{\frac{r^2}{N_R}\,{}^{2}_{A} + \frac{1-r^2}{N_T}\,{}^{2}_{A}} \qquad \textbf{Equation 14-1}$$

Here, σ_A is the standard deviation of the annual mean wind speeds as a percentage of the mean, which we assume is the same for the reference and target sites; N_R and N_T are the number of years of reference and overlapping reference-target data, respectively; r is the Pearson correlation coefficient based on a suitable averaging period (such as daily means); and σ is the uncertainty in the derived historical mean wind speed at the target site.

As described in chapter 12, this equation makes a number of assumptions - the most important of which being that the reference data record is consistent through time, with no discontinuities or trends resulting from changing location, equipment, surroundings, and other factors - and so should be applied with caution. Because of increasing doubts about this assumption for reference data older than, say, 10-15 years, it is best not to allow N_R to exceed 15. In addition, because of seasonal effects, the equation should not be used with much less than one year of overlapping target and reference data.

Even when these conditions are met, actual errors may depart substantially from the equation, as illustrated in Figure 14-1. This chart shows the results of an experiment using data from three tall towers in different parts of the United States. A regression was performed with several surface reference stations around each tower, using a 12-month rolling window of daily mean data. The resulting error margins, calculated for all the 12-month samples for each station relative to the true mean for the tower, are plotted against r^2. The smooth curve is the theoretical uncertainty assuming a standard deviation of annual mean speeds of 3.5%, the mean for the three towers.

Historical wind records suggests the standard deviation of annual mean wind speeds ranges from 3% to 5%, depending on the location and source of data. Without conducting a detailed analysis of available wind records, it is reasonable to assume 4%. With this assumption, and for one year of overlapping data, a reference record ranging from 7-to-15 years, and a correlation factor ranging from 0.6 to 0.9, a typical range of uncertainties in the historical mean speed is 1.6%-2.8%.

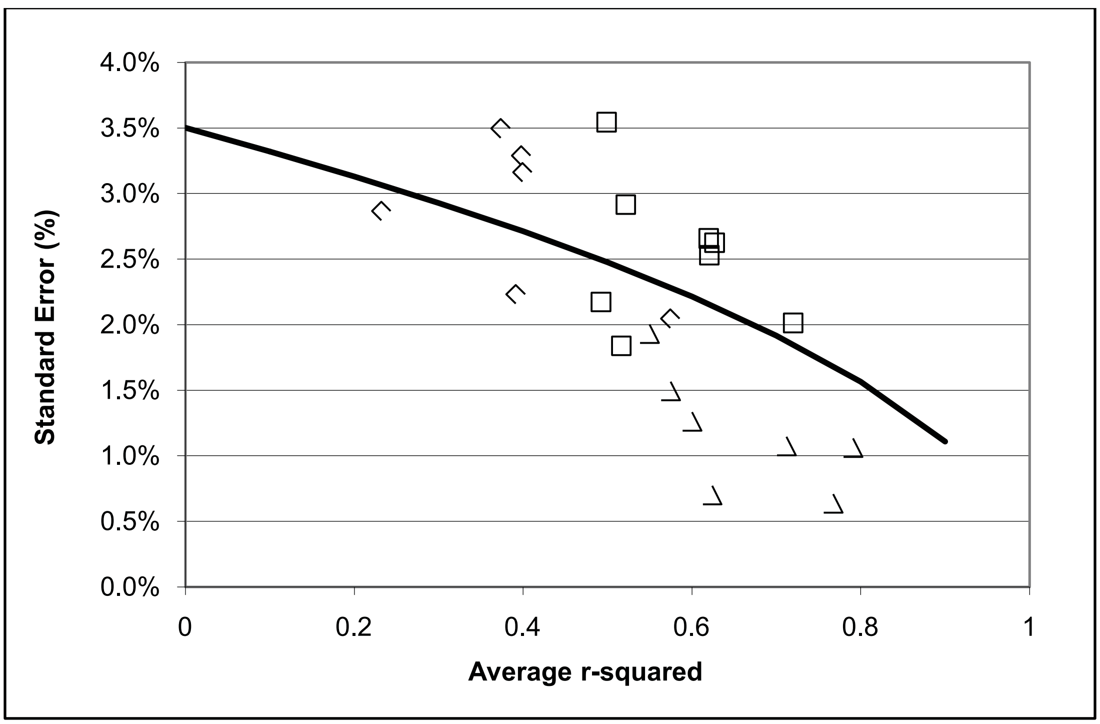

Figure 14-1 - Results of an experiment to determine the uncertainty of MCP based on 12-month unconstrained linear regressions with three towers. Curve is the theoretical uncertainty assuming 3.5% interannual variations. For explanation, see the text. (Source: M. Taylor et al., "An Analysis of Wind Resource Uncertainty in Energy Production Estimates," AWS Truepower, 2004.)

14.3. FUTURE WIND RESOURCE

The uncertainty in the future wind resource can be divided into two components: that due to normal variability in the wind climate, and that due to the risk of long-term climate change. Assuming the two components are unrelated, the individual uncertainties can be combined by the sum of the squares, as follows.

$$\sigma = \sqrt{{}_{normal}^{2} + \sigma_{climate}^{2}} \qquad \textbf{Equation 14-2}$$

For the first component, $_{normal}$, the same interannual variability as that used when assessing the historical climate, e.g., 4%, can be assumed. Adapting the equation from section 14.2, we have:

$$_{normal} \cong \frac{A}{\sqrt{N_P}} \qquad \textbf{Equation 14-3}$$

where N_p is the number of years over which the average is to be calculated - usually 10 or 20.[50] Although the possibility of climate change is more speculative, it should not be ignored. Considering the studies conducted to date (reviewed in chapter 12), we estimate a plausible range of uncertainty from this component to be 0.5%-2%. The lower end of this range applies to a plant life of 10 years, while the upper end might apply to a plant life as long as 20-25 years.

For a plant life of 10 years, the combined uncertainty is 1.4%. Over 25 years, it increases to 2.2%. The climate-change component is negligible in the first instance; leaving it out would reduce the uncertainty by just 0.1%, to 1.3%.[51] It becomes much more important as the project horizon lengthens.

It should be noted that these uncertainty estimates weigh future plant production the same as present production. In a present-value analysis supporting a plant investment decision, plant production - and hence revenues - in the distant future would probably be discounted more heavily than production in the near future. Thus, projections of uncertainty for project lifetimes as long as 20 years may have little relevance for financial modeling, and for this reason, the 10-year uncertainty may be preferred.

[50] The number of years represents the effective project life for the purpose of investment planning. Sometimes an estimate of the uncertainty in the wind resource for any given year is required. For this, $N_p = 1$, and the uncertainty reduces to the interannual variability. In that case, climate-change risk can safely be ignored.

[51] This is a side-effect of the sum-of-the-squares rule. If one of the two uncertainties is much smaller than the other, its impact on the combined uncertainty becomes even smaller. For example, if one uncertainty is 10%, and the other is 1%, the combined uncertainty is not 11% but 10.05%.

14.4. WIND SHEAR

The wind shear uncertainty can be likewise divided into two components: the uncertainty in the observed wind shear due to possible measurement errors, and the uncertainty in the change in wind shear above mast height. The two components are independent of one another, so the sum of the squares applies.
With respect to the first component, the key contributing factors are the uncertainty of the speed ratio between the two heights and the height ratio:

$$\Delta\alpha_{bs,v} \cong \frac{lo\ (1+\ _{r,v})}{lo\ (\ ^{2}/\ _{1})} \qquad \textbf{Equation 14-4}$$

The speed ratio uncertainty, $_{r,v}$, is approximately the uncertainty in the measured speed at each height multiplied by the square root of two. If the uncertainty in the speed ratio is 1.5%, and the upper and lower heights are 60 m and 40 m, the uncertainty in the shear exponent $\Delta\alpha$ is 0.037.

This equation ignores the uncertainty in the heights of the instruments. The contribution of this factor can be estimated from the following equation:

$$\Delta\alpha_{bs,h} \cong \alpha \frac{lo\ (1+\ _{r,}\ )}{lo\ (\ ^{2}/\ _{1})} \qquad \textbf{Equation 14-5}$$

The additional factor of $\propto$, always much less than one, means that the effect of a given uncertainty in the height ratio, $_{r,h}$, is considerably less than the effect of the same uncertainty in the speed ratio. Nevertheless, the contribution may be significant if the instrument heights on the tower have not been accurately determined. In that case, the height-related uncertainty can be added to the speed-related uncertainty through the sum of the squares.

If the shear calculation uses sensors that are mounted differently, such that their exposure to tower effects is not similar, this should be taken into account in the shear uncertainty. The following are examples where differing mounting configurations can contribute to the shear uncertainty: if the uppermost sensors were placed too close to the top of the tower, if the sensors were not oriented in the same direction, and if the ratio of boom length to tower width varies between scenarios.

The second component is more difficult to estimate and depends very much on the site. As a rough rule of thumb, we estimate the uncertainty in the shear exponent above the top of the mast of anywhere from 10% to 20% of the observed shear, depending on the complexity of the terrain and land cover. If the observed shear is 0.20 and the terrain is flat and open, we might assume an uncertainty of 0.02; if the observed shear is 0.30 and the terrain is complex, we might assume 0.06.

With these assumptions, a typical range of uncertainty in the shear exponent is from 0.04 to 0.07. The corresponding uncertainty in the hub height speed is approximated by the following equation:

$$= \mathbf{100}\left[\left(\frac{\quad}{_{2}}\right)^{\Delta} - \mathbf{1}\right](\%) \qquad \textbf{Equation 14-6}$$

For a mast height of 60 m height and hub height of 80 m, the range of uncertainty in speed is 1.1% to 2.1%.

14.5. WIND FLOW MODELING UNCERTAINTY

The wind flow modeling uncertainty [52] is defined as the uncertainty in the average wind speed for the turbine array relative to the observed wind speed at the site masts. The range of uncertainty can be very wide, as it depends on the model used, the model's resolution, the terrain and wind climate, the quality of wind measurements, the placement of the masts, and other factors. It is often not an easy task to estimate it in a rigorous, objective fashion.

In the ideal case, there are enough masts at the site to test the modeling uncertainty directly. Ten or more masts are required for a statistically robust estimate, though in a pinch, as few as five masts may do. The general approach was described in chapter 13: each mast is withheld from the modeling in turn, and a prediction for that mast is made based on the others. The standard deviation of the resulting errors is the estimated error margin for an arbitrary point.

Assuming the proper conditions are met, the uncertainty in the array-average wind speed can be approximated by the equation,

$$\boldsymbol{\sigma} \cong \frac{_{\boldsymbol{m}}}{\sqrt{\boldsymbol{N}}} \qquad \textbf{Equation 14-7}$$

where $_m$ is the error margin calculated in the previous step, and *N* is the number of masts.

This equation describes the ideal case in which the masts are distributed more or less evenly within the proposed turbine array in locations that are representative of where the turbines may be installed. Then the errors in predictions made from the masts can reasonably be assumed to be uncorrelated with one another. Very often, however, these conditions are not met. Sometimes masts are placed in unrepresentative locations - for example, on a ridge top, whereas most of the turbines are to be placed down the slope. Sometimes masts are not distributed evenly throughout the array, but are clumped in one section. In the extreme case where all the masts are well outside the turbine array, little or no benefit is derived from more

[52] This chapter addresses the uncertainty associated with numerical wind flow models, though the methods generally apply to other quantitative models as well.

than one mast, and the model error margin derived from the mast data may be invalid. The only recourse in such situations is to rely on experience and judgment.

As an alternative to Equation 14-7, some analysts choose to divide the array into sections assigned to each mast, estimate the uncertainty separately for each section, and then combine the uncertainties to find the uncertainty for the project as a whole. This method is especially suited to situations in which the masts are unevenly distributed, so that some masts have more turbines assigned to them than others. An important issue is whether the separate uncertainties are treated as independent of one another. If so, then the sum of the squares applies, and the combined uncertainty is lower than the average. Otherwise, a weighted linear combination should be used. The more diverse the mast locations, the more it is reasonable to assume independence.

In practice, errors from numerical wind flow models fall in a very wide range. In simple terrain with little variation in land cover, and with multiple masts, the uncertainty in the array-average speed may be as low as 2%. In more complex situations, uncertainties as high as 10% or more may be justified. A typical range is 3-6%.

14.6. SUMMARY

Table 14-1 summarizes the range of uncertainties in each category and the overall uncertainty range for the array-average wind speed for typical wind projects.

Category	Uncertainty
Measurement Accuracy (single anemometer)	1.3%-2.5%
Historical Wind Resource	1.6%-2.8%
Future Wind Resource (plant life of 10-yrs, 25-yrs)	1.4%, 2.2%
Wind Shear	1.1%-2.1%
Wind Flow Modeling	3.0%-6.0%
Overall (plant life of 10 years assumed)	**4.1%-7.5%**

Table 14-1 Summary of typical uncertainty ranges by category.

APPENDIX A: WIND RESOURCE ASSESSMENT EQUIPMENT VENDORS

All Weather, Inc.
1165 National Dr.
Sacramento, CA 95834
(916) 928-1000
www.allweatherinc.com

Belfort Instrument
727 S. Wolfe St.
Baltimore, MD 21231
(410) 342-2626
www.digiwx.com

Campbell Scientific, Inc.
815 W. 1800 N.
Logan, UT 84321-1784
(435) 753-2342
www.campbellsci.com

Climatronics Corporation
140 Wilbur Pl.
Bohemia, NY 11716
(631) 567-7300
www.climatronics.com

Coastal Environmental Systems
316 Second Ave. S.
Seattle, WA 98104
(206) 682-6048
www.coastalenvironmental.com

Geotech Instruments
10755 Sanden Dr.
Dallas, TX 75238
(214) 221-0000
www.geoinstr.com

Kipp & Zonen
125 Wilbur Place
Bohemia, NY 11716
(631) 589-2065
www.kippzonen.com

LI-COR, Inc.
4647 Superior St.
Lincoln, NE 68504
(402) 467-0700
www.licor.com

Met One Instruments
1600 Washington Blvd.
Grants Pass, OR 97526
(541) 471-7111
www.metone.com

NovaLynx Corporation
P.O. Box 240
Grass Valley, CA 95945
(530) 823-7185
www.novalynx.com

NRG Systems, Inc.
110 Riggs Road
Hinesburg, VT 05461
(802) 482-2255
www.nrgsystems.com

Radian Corporation
461 Cornwall Road
Oakville, ON L6J 5C5
Canada
(905) 844-1242
www.radiancorp.com

R. M. Young
2801 Aero Park Dr.
Traverse City, MI 49686
(231) 946-3980
www.youngusa.com

Rohn Products
6718 W. Plank Rd.
Peoria, IL 61604
(309) 697-4400
www.rohnnet.com

Sabre Industries
1120 Welsh Road, Ste. 210
North Wales, PA 19454
(267) 263-1300
www.sabreindustriesinc.com

Scientific Sales
P.O. Box 6725
Lawrenceville, NJ 08648
(609) 844-0055
www.scientificsales.com

Second Wind Inc.
366 Summer St.
Somerville, MA 02144
(617) 776-8520
www.secondwind.com

Thies Clima
Hauptstraße 76 D-37083
Göttingen, Germany
+49-551-79001-0
www.ThiesClima.com

Tower Systems
P.O. Box 1474
Watertown, SD 57201
(605) 886-0930
www.towersystems.com

Vaisala Inc.
10-D Gill St.
Woburn, MA 01801-1068
(617) 933-4500
www.vaisala.com

Vector Instruments
115 Marsh Road
RHYL, North Wales
LL18 2AB, United Kingdom
www.windspeed.co.uk

Yankee Environmental Systems, Inc.
101 Industrial Rd.
Turners Falls, MA 01376
(413) 863-0200
www.yesinc.com

WindSensor
Søkrogen 9
DK-4000 Roskilde
Denmark
+45-46-38-36-28
www.windsensor.dk

LIDAR EQUIPMENT SUPPLIERS

Catch the Wind Ltd.
10781 James Payne Court
Manassas, VA 20110
(703) 393-0754
www.catchthewindinc.com

Leosphere /NRG Systems
PO Box 0509
Hinesburg, VT 05461
(802) 482-2255
www.lidarwindtechnologies.com
www.nrgsystems.com

Lockheed Martin
135 South Taylor Avenue
Louisville, CO 80027-3025
(800) 449-8736
www.lockheedmartin.com

Natural Power
Malvern Technology Centre
Office E708
St. Andrews Rd.
Malvern, WR14 3PS
England, UK
www.naturalpower.com

SgurrEnergy Ltd.
225 Bath Street
Glasgow, G2 4GZ, UK
+44 (0)141 227 1700
www.sgurrenergy.com

SODAR EQUIPMENT SUPPLIERS

Atmospheric Research Technology (ART)
PO Box 1808
Kailua-Kona, HI 96745
(808) 329-1627
www.sodar.com

Atmospheric System Corp. (ASC)
26017 Huntington Ln. Unit F
Santa Clarita, CA 91355
(661) 294-9621
www.minisodar.com

AQSystem
Mediavägen 18
135 48 Tyresö
Sweden
+46 (0) 8 776 40 86
www.aqs.se

Metek GmbH
Fritz-Straßmann-Str. 4
25337 Elmshorn
Germany
+49 (0) 4121 4359 - 0
www.metek.de

Remtech
2 Red Oak Rd.
St. James, NY 11780
(303) 772-6825
www.remtechinc.com

Scintec Corporation
5950 Shiloh Rd. East, Suite S
Alpharetta, GA 30005
(707) 887-0557
www.scintec.com

Secondwind
366 Summer St.
Somerville, MA 02144
(617) 776-8520
www.secondwind.com

WIND RESOURCE ASSESSMENT EQUIPMENT

The is a list of some of the most common wind resource assessment equipment currently used within the industry, but does not include all potential options.

Cup Anemometers

- Climatronics - F460 Wind Speed Sensor
- Met One - 010C
- NRG Systems - Maximum #40
- Thies - First Class Advanced
- Vaisala - WA15
- Vector - A100LK
- Windsensor - P2546A

Wind Vanes

- Climatronics - F460 Wind Direction Sensor
- Met One - 020C
- NRG Systems - 200p
- Thies Clima - First Class
- Vaisala - WA15
- Vector - W200P

Vertical Prop Anemometers

- Climatronics - M102236 Vertical Propeller Anemometer
- RM Young - 27106 Vertical Propeller Anemometer

Sonic Anemometers

- Applied Technologies - CATI/2
- Campbell Scientific - CSAT3
- Climatronics - 102642 Sonic Wind Sensor
- Gill Instrument - WindSonic 2-D Ultrasonic Anemometer
- Met One - Model 50.5 Solid State Wind Sensor
- Metek – Ultrasonic Anemometer USA-1
- RM Young - Model 81000 Ultrasonic Anemometer
- Thies Clima - Ultrasonic Anemometer 3D
- Vaisala - WS425

SODAR Units

- Atmospheric Research and Technology (ART) - Model VT-1 SODAR System
- Atmospheric Systems Corporation - Model 4000, 3000, 2000
- Metek - Phased Array SODAR
- Remtech - PA0
- Second Wind - TRITON Sonic Wind Profiler
- Scintec Corporation - Flat Array Sodar Acoustic Profiler

LIDAR Units

- Catch the Wind - Vindicator
- Lockheed Martin - WindTracer
- Natural Power - ZephIR Laser Anemometer
- NRG Systems/Leosphere – Windcube
- SgurrEnergy - Galion

APPENDIX B: BIBLIOGRAPHY

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(Bradley, S., CRC Press, 2008)

Comparison of the Performance of Four Measure-Correlate-Predict Algorithms
(Rogers, A. L. et al., 2005, Journal of Wind Energy and Industrial Aerodynamics)

Landowner's Guide to Wind Energy in the Upper Midwest
(N. Lange and W. Grant, Izaak, 1995 Walton League of America; available from Midwest Office, Izaak Walton League of America, 5701 Normandale Rd., Suite 317, Minneapolis, MN 55424)

Measure-Correlate-Predict Methods: Case Studies and Software Implementation
(Thoegersen, M. L., 2007, European Wind Energy Conference)

Permitting of Wind Energy Facilities
(National Wind Coordinating Committee, 2002; available at: http://www.nationalwind.org/publications/siting.htm)

Wind Characteristics: An Analysis for the Generation of Wind Power
(Rohatgi, J. and Nelson, V., Alternative Energy Institute, 1994)

Wind Energy Basics: A Guide to Home-and Community-Scale Wind Energy Systems (2nd Edition)
(P. Gipe, Chelsea Green Publishing, 2009)

Wind Energy Comes of Age
(P. Gipe, John Wiley & Sons, Inc., New York, 1995.)

Wind Energy Explained: Theory, Design and Application
(J. Manwell, J. McGowan, and A. Rogers, Wiley, 2010)

Wind Energy Siting Handbook
(American Wind Energy Association, 2008, available at; http://www.awea.org/sitinghandbook)

Wind Power Facility Siting Case Studies: Community Response
(National Wind Coordinating Committee, 2005, available at; http://www.nationalwind.org/publications/siting/Wind_Power_Facility_Siting_Case_Studies.pdf)

Wind Power: Renewable Energy for Home, Farm, and Business (Revised Edition)
(P. Gipe, Chelsea Green Publishing, 2004)

Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering
(D.A. Spera, Editor; ASME Press, New York, 1994: available from The American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017)

APPENDIX C: ADDITIONAL RESOURCES

Freely Available Sources of GIS Data Related to Wind Resource Assessment

Data Type	Web Address
FEDERAL	
USGS Seamless Data Server	http://seamless.usgs.gov/index.php
STATE	
State GIS Clearinghouses	http://web.mit.edu/dtfg/www/data/data_gis_us_state.htm
State GIS Clearinghouses	http://www.columbia.edu/acis/eds/outside_data/stategis.html
State & Federal GIS Clearinghouses	http://ncl.sbs.ohio-state.edu/5_sdata.html
SPECIFIC GIS DATA SITES	
National Wetlands Inventory	http://www.fws.gov/wetlands/Data/mapper.html
Free Orthoimagery Sources	http://worldwindcentral.com/wiki/Sources_of_free_orthoimagery
Great Lake Information Network	http://gis.glin.net/ogc/services.php?by=topic
FCC Data	http://wireless.fcc.gov/geographic/index.htm?job=home
Gas & Oil Data	http://www.mapcruzin.com/download-free-energy-maps/free-energy-arcgis-shapefiles.htm
WIND RESOURCE DATA	
Local Universities	Various
NOAA's National Climatic Data Center	http://gis.ncdc.noaa.gov/Portal/
NREL Wind Power Data	http://www.nrel.gov/gis
NREL Western Wind Resources	http://www.nrel.gov/wind/westernwind
State Climate Offices	http://www.stateclimate.org
Wind Powering America	http://www.windpoweringamerica.gov/wind_maps.asp

Additional Sources of GIS Data Related to Wind Resource Assessment

Type	Web Address
GENERAL	
GIS Data Clearinghouse	http://data.geocomm.com
Landcover Data	http://www.mdafederal.com/home
WIND RESOURCE DATA	
AWS Truepower's windNavigator	http://windnavigator.com
3Tier	http://www.3tiergroup.com

For information on other
NYSERDA reports, contact:

New York State Energy Research
and Development Authority
17 Columbia Circle
Albany, New York 12203-6399

toll free: 1 (866) NYSERDA
local: (518) 862-1090
fax: (518) 862-1091

info@nyserda.org
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