IRENA
International Renewable Energy Agency

WIND RESOURCE MEASUREMENT: GUIDELINES FOR ISLANDS

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GUIDELINES FOR ISLANDS

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1 INTRODUCTION

This book describes how to plan and conduct a high-quality wind resource measurement campaign on islands. It embodies the collective knowledge of a highly experienced team of wind resource engineers and meteorologists who are fully conversant in the requirements for developing modern wind energy projects in both remote and grid-connected settings. It is intended to be used by a wide variety of stakeholders: by funders and investors to establish standards of resource measurement campaigns for projects they finance; by local government agencies, power companies, and developers for planning and conducting a high-quality measurement programme; by programme managers to support equipment procurement, installation, operations and maintenance, and data collection; and by field engineers and technicians charged with installing and operating wind measurement equipment and collecting and analysing the data.

In the chapters that follow, the important elements of a successful island-based resource measurement campaign are described in detail. First, however, we think it might be helpful to address several questions. Why measure the wind? Why focus on islands? Why follow these guidelines? And how should this document be used?

1.1 WHY MEASURE THE WIND?

Good wind resource measurements are essential to the success of almost any wind project of a significant size.[1] They play several important roles.

First, and most obviously, they provide the inputs needed for accurately estimating the plant's energy production. This is a concern of all project stakeholders, including developers, investors, lenders, and power companies. Even consumers have an interest, as they may be affected by rising costs or power interruptions if projects do not perform as expected. The potential impacts of inaccurate resource assessment are especially acute in areas, like some islands, with constrained electrical systems.

Second, they affect the design of the wind project, including such fundamental aspects as the placement of the turbines and the selection of a suitable turbine model. For example, the directional distribution of the wind resource affects the optimal layout of turbines to minimise interference – the so-called wake effect – between them. Also, the speed distribution, turbulence characteristics, and other aspects of the resource determine the turbine suitability class, which is

[1] Exceptions to this rule can include very small projects, where the benefits of a resource assessment campaign may be outweighed by its costs, and sites where sufficient resource data to estimate energy production accurately are already available from other sources (nearby wind projects, for example). Such situations must be assessed case by case.

considered by the manufacturer in deciding whether to warrant a particular turbine model for the site. No lender or investor will finance a project without the manufacturer's warranty that it will operate reliably.

Beyond these direct benefits, a high-quality wind resource measurement programme can ease many hurdles in the wind plant development process by reducing the project's perceived risk, as well as encourage interest in the project from governmental and utility partners, developers, and local communities. While the process is not without costs and challenges, it is a rare wind project that would not benefit from appropriate investment in good resource measurements.

Finally, monitoring systems deployed during resource assessment campaigns and kept in operation can provide valuable wind and weather information during and after project installation. The data from these stations can support project construction and power forecasting, as well as performance assessments and operations and maintenance efforts.

1.2 WHY FOCUS ON ISLANDS?

With few exceptions, the technology needed for measuring the wind resource is the same everywhere. Why, then, a manual specifically for islands?

A factor to consider is that wind plants tend to be smaller and employ smaller turbines than onshore projects in mainland environments. This means an island wind measurement campaign can often make do with shorter and fewer towers and other measurement systems.

In addition, quite often, islands experience more extreme and different weather conditions than other sites, calling for modifications in measurement techniques. For example, on islands that frequently experience powerful ocean storms, the ability to quickly lower equipment may be beneficial. Exposure to sea air can cause rapid corrosion of components, as well as (in cold climates) heavy icing.

Finally, islands and other isolated or remote communities ("virtual islands") – especially those with developing economies –often face technical and financial constraints relating to their isolation, size, and stage of economic development, which can influence how a resource measurement programme is designed and conducted. The constraints may include:

- Financial Resources: Ensuring a high quality of data is essential, but limited financial resources must be considered in many cases. A gold-plated approach requiring more investment than the community is capable of sustaining may not be successful.

- Economic development: Import duties and shipping costs are often high for islands and remote communities. By enabling local firms to participate in the project, *e.g.* through contracts to erect lattice towers, the programme can reduce costs and build community support.

- Technical resources: The limited availability of trained technical staff argues for relying on simple, robust equipment requiring little maintenance and support. One example is to use fixed lattice towers, which can be locally built and climbed by one person, rather than tilt-up tubular towers, which are likely to be imported and require a crew to raise and lower them.

- Data communications: Islands and remote communities may have limited or no cellular telephone coverage. In such situations, it may make sense to emphasise on-site rather than remote data collection.

While it is important to be aware of the constraints often faced by islands, it is equally valuable to recognise the benefits that can be realised from island wind projects. For example, many islands and remote communities rely on imported diesel fuel for electrical power, which can result in much higher electricity prices than in grid-connected areas. In such situations, even unsubsidised wind power can be cost effective. Further benefits can be realised from the diversification of power supplies, especially in storm-prone regions or areas with seasonal access constraints. Integration of wind can help to stabilise power costs, generate local jobs, and reduce export of local currency for fuel purchases.

With expert guidance and training, it should be well within the capabilities of most island communities to carry out wind measurement campaigns that meet the needs of financing institutions and other stakeholders. Although much of the information needed is available in the published literature, it is scattered in many different locations (web sites, technical reports, books), and some of it is not applicable or must be modified to island conditions. In these guidelines, we pull the information together in one place and adapt it to island settings.

1.3 WHY FOLLOW THESE GUIDELINES?

The accuracy and reliability of wind resource measurements has a direct impact on wind plant design, turbine selection, and energy production estimates. If you want to know, with good accuracy, which turbines to install, where to put them, and how much electricity your wind turbine or power plant is going to produce, you have to measure the resource at the site, including at a minimum the wind speed, wind direction, and temperature.

Of these parameters, by far the most important is the wind speed. On the face of it, obtaining an accurate measurement of wind speed is not difficult. The technology 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.

However, accurate resource measurement depends on much more than observing the wind speed at a particular time and place. How many anemometers are used, their heights and orientation, the way they are mounted, the frequency and types of data collected, and the additional sensors needed to measure temperature and other parameters – these are just some of the issues requiring careful consideration. New technologies such as sodars and lidars have recently come on the scene, as well, and they raise a host of new challenges and opportunities.

Additionally, challenges can be presented when integrating the variable generation of wind power onto smaller (or isolated) electrical systems such as those found on islands. Good resource data can help support studies to address these challenges. Establishing the time-varying characteristics of the wind resource is important for utility companies when they plan for new generation, as they influence how much other, non-wind capacity, as well as fast-response reserve units, are required for reliable power supply. Such information can also help determine loads on transmission and distribution lines and the potential need for transmission and distribution system upgrades. All of these considerations, along with the predicted total energy output of the wind plant, can affect the project's overall cost, profitability, and feasibility.

Mistakes made at this early stage of developing a wind project can mean the plant will fail to meet its forecasted production or experience excessive downtime, repairs, and other operational challenges. Since these factors affect project revenues and costs, the institutions involved in financing wind projects pay close attention to the quality of the wind measurement campaign. Such institutions come in several types:

- Banks and other lenders provide debt financing, or loans. A loan to finance a wind project is similar to a home mortgage or car loan, though the amounts involved are much larger, of course. The plant owner is required to pay back the loan according to a pre-determined schedule. To protect their money, banks look closely at the ability of the project to make payments even when production is low, such as in low-wind periods. For this reason, loans typically cover only a portion of the project cost, a fraction referred as the debt-equity ratio.

- In private financing, equity investors usually provide the rest of the capital to build the project. Equity investments are riskier than loans, since investors only begin to earn money once the loan payments are met. In exchange for the added risk, investors expect a higher return than banks typically do. Some equity investors invest in a project at an early stage in order to sell it to other investors before it goes into operation. Others prefer to continue to own a portion of the operating plant and depend on the revenues for their investment return.

- Public financial institutions such as the international development banks (including the World Bank, Asia Development Bank, Africa Development Bank, Inter-American Development Bank, and others), as well as funds from donor countries, provide another source of capital. Such institutions often accept more risk than banks or offer loans at a below-market rate of interest. Sometimes they front early-stage project development, which bring projects to a stage where they can acquire financing from private sources.

- Electric utility companies often develop and own their own wind power plants, typically financing them off their balance sheets, *i.e.* from their general revenues. Though this is often easier than going through external financing channels, such companies, too, are accountable to their owners, and therefore impose tight standards on their capital investments.

Whatever the source of capital, financial institutions demand a high degree of reliability and credibility in the resource estimates on which wind project financial models are built. Without confidence in the quality of the data, lenders and investors will demand a higher return, raising the cost of the project and the price charged to customers – or they may choose not to invest at all.

The need to maintain high standards is one of the key lessons from previous resource measurement campaigns, both on islands and elsewhere. Past programmes have often suffered from a variety of problems including:

- Placement of measurement systems in locations that are obstructed or otherwise not representative, giving a misleading indication of the potential wind resource in the surrounding area
- Gaps and poor data quality caused by sensor failures and a lack of instrument redundancy
- Errors in wind measurements due to substandard mounting and installation practices
- A failure to maintain the equipment and retrieve and store the collected data with acceptable regularity and according to the necessary standards.

Helping islands avoid these and other pitfalls is one of the main objectives of this book. If you follow the rules and procedures described here, your chances of developing a successful project will be greatly improved.

1.4 HOW TO USE THIS MANUAL

This book is organised according to the sequence of steps followed by most wind resource measurement programmes (Figure 1-1).

- Chapter 2 starts with the definition of the overall programme – its goals, requirements, main stages, and project team.
- Chapters 3 and 4 together cover the basics of wind resource assessment, including where winds come from and the factors influencing winds on islands, the definition of wind resources, parameters to be measured, and their relationship to turbine and plant output.
- Chapter 5 covers the selection of sites for wind projects and wind monitoring
- Chapter 6 describes the design of a measurement programme, including such aspects as the number and placement of measurement systems.
- Chapter 7 addresses the different types of tall towers, sensors, and their associated equipment.
- Chapter 8 considers remote-sensing systems, a relative newcomer to the field of resource measurement.
- Chapters 9 and 10 provide detailed information on the installation, operations, and maintenance of monitoring systems.
- Chapter 11 describes methods of storing, retrieving, and protecting data.

- Finally, Chapters 12 and 13 describe the quality control and validation procedures that should be applied to the data, and the types of reports and analytical results that can be produced to summarise the results of the resource measurement campaign.

At the end of each chapter, a short list of "Points to Remember" is presented. This serves as a brief summary of the chapter and highlights important considerations. It can also be used as a teaching or training tool. Since one of the main aims is to provide practical guidance to the people carrying out the programmes, we make use throughout the book of photographs and illustrations and provide checklists, forms, and other tools to help document and verify the proper execution of key steps.

Note this guide focuses only on the resource *measurement* phase of wind resource assessment. There are many other steps involved in wind resource assessment, including such tasks as extending short-term measurements to the long-term historical norm (also called MCP, for measure-correlate-predict); extrapolating measurements from the tower sensor heights to the turbine hub height; performing wind flow modelling; selecting an appropriate turbine model and designing a turbine layout; estimating wake and other losses, and finally estimating the expected net energy production and its uncertainty.

The end point of this process is often a "bankable" energy production report that can be used as the basis for project financing and investment decisions. It is usually performed by an experienced consultant. However, it is helpful for everyone involved in resource assessment to understand the steps. For information on these topics, the reader should seek out some of the references cited in this book. A comprehensive guide to the entire process is provided in-

Wind Resource Assessment: A Practical Guide to Developing a Wind Project (Wiley, 2012).

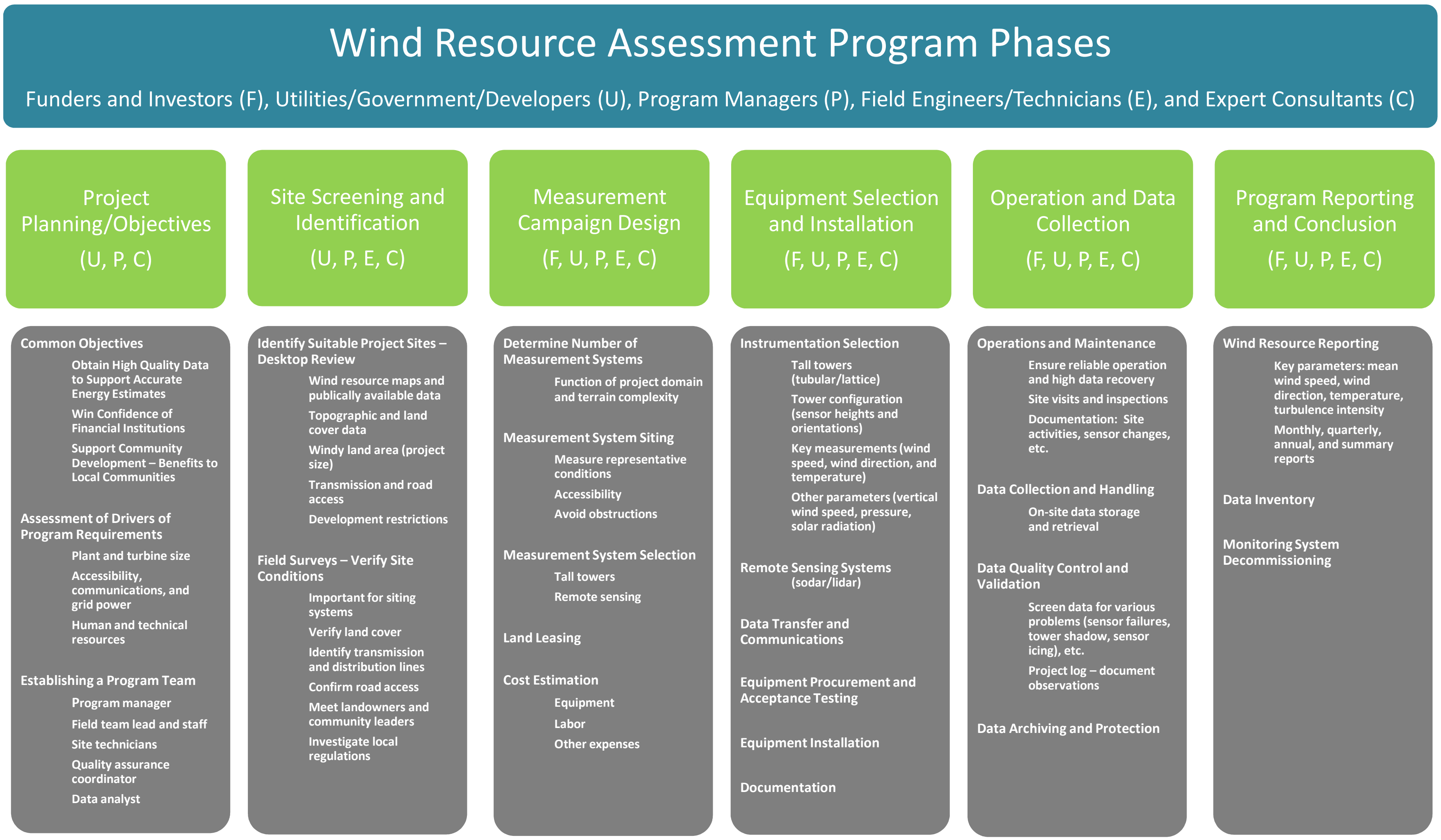

Figure 1-1 The main phases of a wind resource measurement campaign, with user guide. (Source: AWS Truepower, 2014)

2 DEFINITION OF AN ISLAND WIND RESOURCE MEASUREMENT PROGRAMME

A successful wind resource measurement programme starts with establishing clear objectives and developing a sound programme plan to satisfy them. This chapter describes some common programme objectives, factors that can drive programme design, the main stages of measurement campaigns, and the roles and responsibilities of the various project team members.

2.1 OBJECTIVES

Most wind resource measurement programmes seek to satisfy a number of objectives. The most immediate of these is to *obtain sufficient high-quality data to support an accurate estimation of the energy production potential, as well as the design and turbine selection, for the proposed or planned wind project*. Meeting this goal requires close attention to technical details such as the number and types of instruments to be used, their placement within the project area, the length of the monitoring period, accepted instrument-mounting practices, and methods of screening and analysing the data. A wind measurement campaign should be a minimum of 12 months in duration; typical campaign lengths range from 12 to 36 months or longer. Ensuring that team members have all the information they need to satisfy this objective is the main focus of these guidelines.

Other goals may be just as important to the design of the programme, however. For most projects, *winning the confidence of financial institutions* from whom project funding is to be obtained is key. One way financial institutions manage their risk is to insist that the measurement programme be conducted according to established protocols. Where funds are being provided up front to pay for the measurement campaign, this can be a condition of a request for proposals (RFP) for measurement services. When funding is sought after the measurement campaign is completed, an independent consultant may be hired to verify that the required standards were met. Providing the information the consultants need to render judgment is one of the main reasons these guidelines insist on full documentation of every major step in the programme.

Another goal, especially in less-advanced economies such as on many islands, may be to *support community development and capacity building*. Both wind energy projects and the resource measurement programmes that prepare the way for them can benefit local communities. Land owners receive payments for the use of their land, local firms may build and install towers, and local residents may be hired to provide security, check on equipment, and perform maintenance and data collection tasks. Making community development and capacity building an explicit goal of the campaign can help ensure that any such opportunities are fully realised, and that, in turn, can help secure community support – never a bad thing for a nascent wind energy project.

Capacity building means ensuring that at least some of the skills needed to carry out a high-quality measurement campaign are transferred to personnel within the communities. The science and engineering programmes of local universities are often a source of technically skilled staff, who once trained in methods of resource assessment can train others. The skills needed to build and erect lattice towers and instrument mounting equipment are easily learnt by firms that already supply radio and cell towers. Such knowledge transfer helps foster a sustainable wind energy programme that will reduce costs and logistical hurdles for future projects.

2.2 DRIVERS OF PROGRAMME REQUIREMENTS

An early assessment of the key drivers of programme requirements is essential for developing an effective measurement plan. While the drivers may vary between islands, they typically include the following:

- Plant size. Large wind plants typically require measurements at more locations across a project area, thus increasing the measurement budget. While the final plant design cannot be established until after the resource measurement campaign is completed, it is important to develop a rough concept to guide the measurement plan. The maximum rated capacity of the project can be dictated by several factors, including the cost of traditional generation, power company expansion plans, the available capacity of the electrical system, and the size of the prospective project area. In island settings, a wind project size range of 1 MW to 30 MW is typical, although both smaller and larger plants have been installed.

- Turbine size. Larger turbines typically demand measurements at greater heights – either using taller towers or ground-based remote sensing systems. The largest turbines these days are rated at 2 MW to 3 MW each and have hub heights and blade spans of 80-100 m or more. The larger the turbine, however, the more difficult it may be to transport it to the site and erect it. The length of blades and tower sections, for example, determines the minimum turn radius for the trucks carrying them, and may make some roads impassable with the blade and turbine in tow. Furthermore, there must be a sufficiently large open area at each turbine location to lay the blades flat before they can be lifted into place. Very tall cranes are required to lift large turbine components. In contrast, smaller turbines can be more easily transported and installed with locally available equipment on existing roads.

- Communications, power, and other infrastructure. The ability to access sites by road, as well as the availability of cellular data transmission, can have a strong influence on the design of a measurement programme. For specialised applications or large equipment loads, access to grid power or on-site generation may also be a consideration. At remote, difficult-to-access sites, it may not be practical to erect very tall towers or use power-intensive equipment (such as sodars or lidars). Where cellular reception is poor, it may be necessary to rely on manual data retrieval or (usually more expensive) satellite communication.

- Human and technical resources. The availability of a sufficiently skilled workforce will have bearing on the makeup of the project team. People with an engineering or similar technical background should, with training, be able to carry out all of the tasks described in this book. If such skills are absent, it would be advisable to call on experienced consultants to supervise and carry out portions of the work. At the same time, there are numerous roles non-technical staff can play, such as providing manual labour for tower and equipment installation, fence-building, security, and so on.

- Risks of vandalism and theft. Where equipment is at substantial risk of vandalism or theft, it may be prudent to take precautions such as fences and security guards. In addition, equipment such as data loggers should be mounted out of easy reach.

2.3 STAGES OF A WIND RESOURCE MEASUREMENT CAMPAIGN

The rest of this report gives a detailed description of the various elements of a typical wind measurement campaign. Here we provide a preview, with references to the chapter or chapters where each topic is addressed in depth.

Site Screening and Identification

The first stage of the campaign is usually to identify prospective wind development sites and select one or more of them for resource monitoring. The site selection may consider a number of attributes. The expected wind resource is almost always one of these. Others include constructability, access, and environmental or cultural constraints and sensitivities. Initially, and depending on the size of the island, the screening can be done remotely using wind maps and publically available data in a geographical information system (GIS). The remote screening is then followed by visits to the site to verify and acquire additional information, narrow down the list, and select locations for monitoring systems. Details on site screening are provided in Chapter 5.

Measurement System Selection and Placement

Site selection is followed by the design of the measurement campaign. This includes selection of the measurement systems – whether towers or ground-based remote sensing systems – and their placement within each proposed project area. Meteorological towers and remote-sensing systems should be sited in such a way as to minimise the uncertainty of the wind resource where turbines are likely to be installed. The distance from the system to the turbines is one consideration; the similarity or representativeness of the terrain is another. Additional information regarding the proper placement of meteorological masts is provided in Chapter 6.

Tall Towers

The mainstay of most wind monitoring programmes is the tall tower. At large mainland projects, several towers of 60 m to 100 m height are commonly used. However, for small island projects, a single 30 m to 50 m tower may suffice.

Tall towers are instrumented with sensors to measure, at a minimum, horizontal wind speed, wind direction, and air temperature (from which air density can be derived). Optional sensors include solar radiation, air pressure, and vertical wind speed. Redundant anemometers and direction vanes are recommended to ensure a high data recovery. In addition, wind speed measurements at multiple heights are needed to determine the wind shear, or rate of change in wind speed with height. Descriptions of different tower types and recommendations for standard instrumentation packages are presented in detail in Chapter 7.

Ground-Based Remote Sensing

Ground-based remote sensing systems are a relative newcomer to resource assessment. The two main options are sodar (sonic detection and ranging) and lidar (light detection and ranging). Three key advantages of these systems over towers are that they are mobile, relatively easy to install, and can measure winds up to 150 m or 200 m above ground level, well above the height of most tall towers. On the downside, however, they are more expensive and require more expert maintenance as well as larger power supplies than most instrumented tall towers. Currently, remote-sensing systems are most often used to complement tower-based measurements, though their acceptance as the sole source of wind resource measurements is growing. They are covered in Chapter 8.

System Installation

The installation of the measurement systems can proceed once the site selection and wind monitoring system design have been completed, all required permits and land lease or use agreements have been obtained, and the equipment has been acquired. Chapter 9 provides guidance on the main installation steps, including equipment procurement, inspection and preparation; tower or remote-sensing system installation; sensor and equipment installation; site commissioning; and documentation.

Before installation, the 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 minimises the influence 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.

Station Operation and Maintenance

Diligent maintenance of equipment and careful documentation are necessary to achieve a high quality of data and preserve the integrity of the measurement campaign. It is recommended that a simple but thorough operation and maintenance plan be implemented. This plan should incorporate various quality assurance measures and provide procedural guidelines for all programme personnel. Specific recommendations for the operation and maintenance of wind resource monitoring stations are provided in Chapter 10.

Data Collection

The data collection and handling process ensures that once the measurement campaign is under way, the data recorded by instruments are regularly retrieved, made available for analysis, and protected from corruption or loss. Chapter 11 provides background information on data storage and retrieval methods as well as guidelines for carrying out the process. Appropriate documentation is essential, as it provides the basis for subsequent data screening and quality control. Suggested data transmission documentation is provided at the end of Chapter 11.

Data Validation and Reporting

Once data collection begins, the data must be screened and reviewed often and summarised periodically. The goals of this stage are twofold. The first is to ensure that any problems are quickly identified so that the equipment can be repaired or replaced, if necessary, with a minimal loss of data. This entails the frequent application of a basic, and usually automated, quality-control (QC) procedure. The second is to produce a high-quality data set for subsequent analysis supporting the design of the wind project and estimation of its energy production. This second task generally involves a manual review of the data to supplement the automated QC procedures, as well as summary descriptions of the data. These steps are detailed in Chapters 12 and 13.

Decommissioning

Once the measurement campaign has been completed, the equipment may be decommissioned, or removed from the site, and repurposed elsewhere. (These tasks are not covered in this book.) Where it is likely that a wind project will be built, however, it is generally recommended that at least one measurement system remain in operation to provide a consistent baseline for comparison of the resource before and after plant construction.

2.4 THE PROGRAMME TEAM

A qualified and engaged programme team is a prerequisite for a successful wind resource measurement programme. Each person involved should be fully briefed on his or her role and its relation to the achievement of the programme goals. The following lists the main roles to be performed. In smaller programmes, some roles can be carried out by the same person. Other team members or experts can fill roles such as siting and system specification, and can be consulted at the request of the programme manager.

- Programme manager. The programme manager has overall responsibility for planning, budgeting, and executing the measurement campaign. He or she should have training and experience in project management, as well as familiarity with the principles of wind resource assessment. The programme manager should be involved in all decisions involving the measurement campaign, and may also serve as the local liaison, or project champion, in which role he or she is responsible for community interaction, support, permitting, land leases, and other tasks.

- Field team lead. The field team lead is in charge of the installation of all equipment, including towers, instruments, power supplies, and remote-sensing systems, and may also be responsible for maintaining the equipment in the field. He or she is also responsible for ensuring that field staff follow all applicable safety protocols, especially when working around or climbing towers. He or she should have practical experience in wind measurement, as well as a background in engineering or a related technical discipline.

- Field staff. They support the field team lead in installing and maintaining equipment. Prior technical training in wind resource assessment is useful but not essential for most tasks; however, familiarity with tower and equipment installation and safety protocols is essential.

- Data retrieval and basic maintenance technician. Where remote data retrieval is not possible, someone may be designated to go to the project site to retrieve the data manually. In the process, he or she can carry out basic system checks, such as verifying that instrument booms are straight and guy wires have the right tension, and notify the field team lead of problems. Most people can acquire the necessary skills through training, regardless of educational background.

- The data analyst performs the QC checks on the data, generates validated data sets, and prepares summary reports for review by the programme manager and programme sponsors. An understanding of the principles of wind resource assessment and good skills in spreadsheets or computer software are desirable for this position.

- Quality assurance coordinator. An essential part of every measurement programme is the quality assurance plan, an organised and detailed action agenda for guaranteeing the successful collection of high-quality data. The quality assurance coordinator ensures that this plan is properly implemented. In addition, the coordinator should maintain the project documentation in an organised fashion. Ideally, this person will have a good technical background and be knowledgeable of the routine requirements for collecting valid data.

2.5 ROLE OF OUTSIDE EXPERTS

Outside experts can provide valuable input for island wind resource measurement programmes. Where local team members lack experience and technical training, it is essential that experts be consulted at every stage of the process. They may initially assume some of the main team roles and train other team members. As the local programme team members gain experience and skills, they can assume more responsibility, while their decisions and actions continue to be reviewed by experts. Eventually the programme team may no longer need expert support. However, it is never a bad idea for a measurement programme to be reviewed periodically by independent specialists to ensure that its goals continue to be met.

Outside experts can come from many different sources, including government agencies, universities, wind project developers, turbine manufacturers, measurement equipment vendors, and private consultants. Many such entities have made available publications and information which can be of use in training team members and improving their skills. The cost of outside experts (including travel and labour) is an important consideration in defining the programme budget. In addition, it is prudent to select experts who have experience in island environments and who are in a position to give the programme the time and attention it deserves.

2.6 POINTS TO REMEMBER

- The most critical objective of a wind measurement campaign is to obtain sufficient high-quality data to support an accurate estimation of the energy production of the proposed or planned wind project. Numerous related goals offer both challenges and opportunities for project stakeholders.

- Key factors that help define monitoring programme requirements include the anticipated project and turbine size, site accessibility, and availability of human, technical, and capital resources.

- Measurement campaigns are divided into six to eight distinct stages. Each stage requires careful planning by the programme team.

- The composition of the programme team plays an important role in the eventual success of the measurement campaign. Key roles include the programme manager, field team lead, field staff and operations and maintenance technician, data analyst, and quality assurance coordinator. Some roles can be performed by the same person. In addition to leading the overall effort, the programme manager should act as a local "champion," establishing and maintaining contacts with affected communities to facilitate campaign logistics and encourage local support.

- The advice and direct involvement of outside experts are important to the success of most wind resource measurement programmes, especially where local staff lack experience and technical skills. As local team members acquire experience and training, the involvement of outside experts can be reduced. However, it is recommended that periodic reviews by independent specialists be conducted to ensure the programme's goals continue to be met.

3 UNDERSTANDING THE WIND RESOURCE

Assessing the wind resources of islands benefits from a basic knowledge of what causes and influences the wind. Such knowledge is useful for selecting promising wind project sites, choosing what and where to measure, and forming a concept of the extent and layout of the wind project. What follows is a primer on the origins and driving factors of the wind. We encourage you to do your own research, particularly on the meteorology of your region, using the many resources available in books and on the Internet.

3.1 GLOBAL CIRCULATIONS

The main cause of wind is *pressure gradients*, or differences in pressure between different parts of the earth's surface; picture the highs and lows on a weather map. A mass of air tends to move *towards* a zone of low pressure and *away* from a zone of high pressure. Left alone, the resulting wind would eventually equalise 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 heating and cooling of the earth's surface. When the surface heats up – on a warm sunny day, for example – the air above it expands and rises, and the pressure drops. When there is surface cooling, the opposite 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 somewhere on the planet.

While uneven solar heating is ultimately the driving force, the earth's rotation plays a key role in shaping wind patterns. Away from the equator, the *Coriolis effect*[2] causes moving air to turn clockwise in the northern hemisphere and counter clockwise in the southern hemisphere, relative to an observer on the ground. Its influence means that the wind rarely moves directly towards a zone of low pressure, but rather circles around it. This is the origin of the cyclonic winds in hurricanes and typhoons.

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

[2] The Coriolis effect is a property of observing motions from a rotating reference frame – in this case the earth. One way to understand it is that the earth's surface moves faster around the axis at the equator than it does closer to the poles. If an object moves freely towards 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.

easterly[3] trade winds, which occur within about 30° latitude around the equator, as well as the mid-latitude westerlies (Figure 3-1). Most tropical islands lie in the trade winds, which tend to be moderate and blow out of the northeast in the northern hemisphere and southeast in the southern hemisphere. The westerlies dominate the wind resources of the temperate latitudes of North America and Europe, as well as the southern extremes of Africa, South America, and Australia.

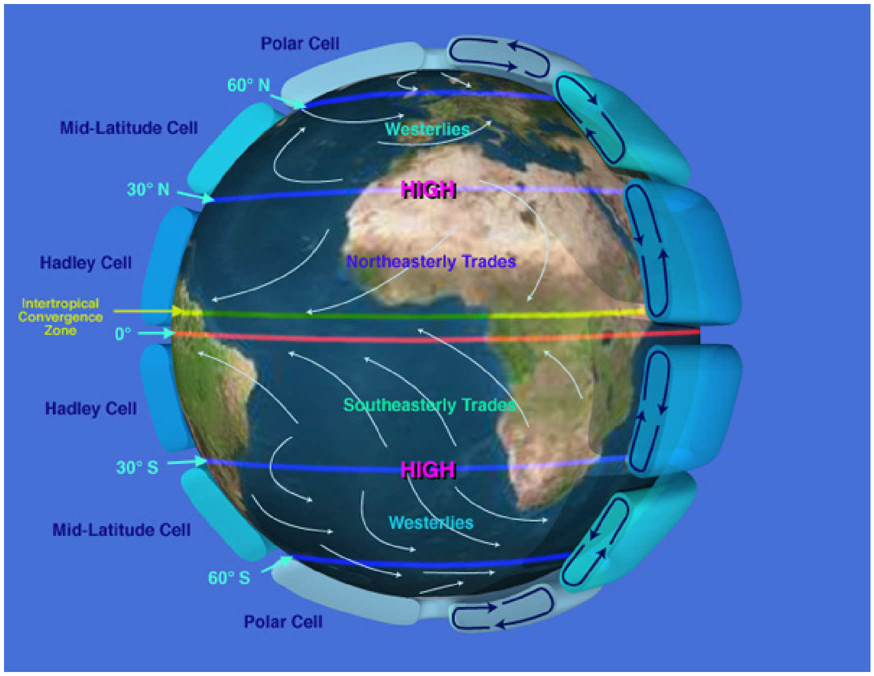

Figure 3-1 The main global atmospheric circulations. (Source: NASA/JPL-Caltech)

3.2 MESOSCALE CIRCULATIONS: MONSOONS AND SEA BREEZES

Superimposed on these global circulation patterns are various regional patterns. Land tends to heat up and cool down more rapidly than the oceans, resulting in daily and seasonal temperature differences. 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 and pressure gradients set up what are called *mesoscale atmospheric circulations* – mesoscale because they are in between the global scale and the local, or micro, scale.

Probably the most familiar and important mesoscale circulation for many islands is the monsoon cycle. Monsoons are wind circulation patterns driven by temperature differences between continents and the surrounding oceans. The most powerful monsoons occur around the periphery of Asia. In South Asia, for example, the summer monsoon (from roughly June through September) is marked by winds from the west and south which pull moisture off the oceans,

[3] By convention, wind direction is denoted by the direction the wind comes *from*. If the air is coming from the south and moving towards the north, it is said to be a southerly wind.

creating heavy rainfall across most of the region. In the winter, the wind reverses direction and comes off the land from the north and east, producing the region's dry season. Other notable

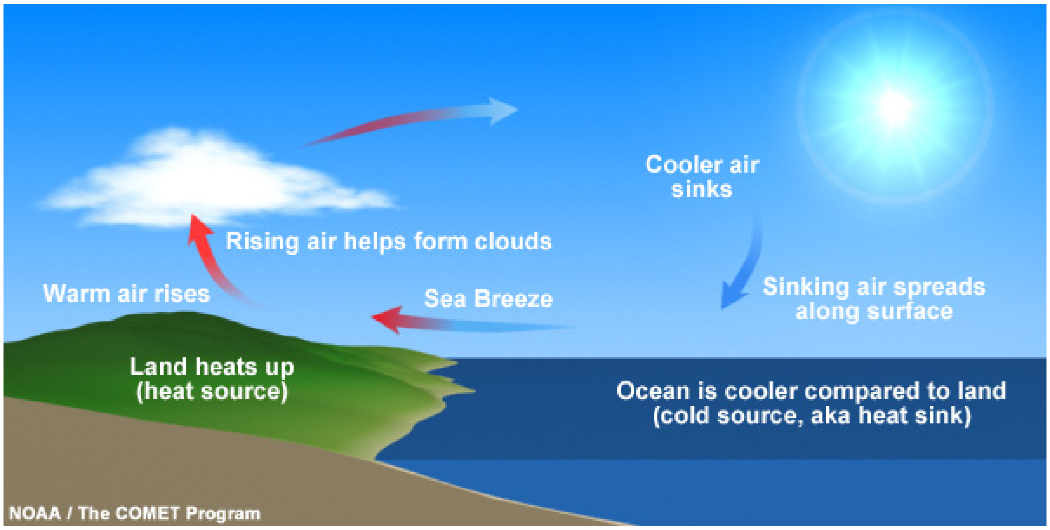

Figure 3-2 Sea breeze circulation (Source: NOAA)

monsoon examples include the East Asia, Australia, and West Africa monsoons.

Monsoons are a continental-scale manifestation of a phenomenon experienced by many islands: 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 fairly weak (and land breezes even weaker), 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 the western United States and Spain, among other locations (Figure 3-2).

3.3 LOCAL INFLUENCES OF TERRAIN AND LAND COVER

Aside from the global and mesoscale circulation patterns, winds can be strongly influenced by topography and land surface conditions. Where the wind is driven over a rise in the terrain - and especially over a ridge that lies perpendicular to the flow – there can be a significant acceleration

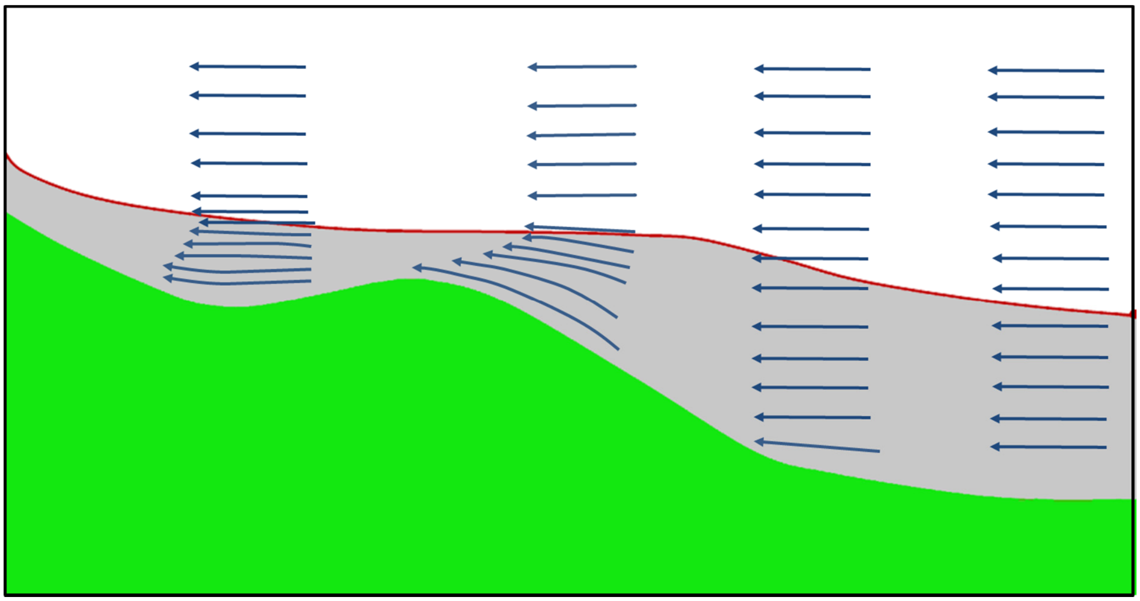

Figure 3-3 Schematic of wind flow forced over a rise in terrain (not to scale). The increase in wind speed is indicated by the tightening and lengthening of the wind arrows. The red line represents the top of the boundary layer (shaded), above which the influence of terrain and surface diminish rapidly. (Source: AWS Truepower)

as the air is "squeezed" through the restricted vertical space (Figure 3-3). As a consequence, many of the best wind sites, on islands as well as on the continents, are on elevated terrain features of some kind – hills and mountains, plateaus and mesas, and ridges.

Elevated terrain does not always produce stronger winds, however. It depends on the characteristics of the wind flow and the height of the terrain. Tropical islands exposed to trade winds are an important case in point. One of the chief characteristics of trade winds is that they are relatively shallow – typically about 1000-2000 m deep over the earth's surface. This layer is topped by a so-called inversion where the temperature abruptly increases, thus "trapping" the winds beneath it (Figure 3-4). If the terrain is much lower than the height of the inversion, then the trade wind can flow over it easily, producing the familiar pattern of windy hilltops and ridges.

However, where island mountains approach or protrude above the inversion, the trade wind is likely to be blocked and diverted around the high terrain through any gaps it may find. This can result in strong winds near sea level. Hawaii, with its mountains extending to over 4000 m elevation, is a good example of an island system within the trade wind zone that exhibits strong blocking and channelling of the wind (Figure 3-5).

The Hawaii example illustrates how the temperature profile of the atmosphere – the change in temperature with height – can affect the wind's response to terrain. The temperature profile determines the thermal stability, or equivalently the buoyancy, of the boundary layer.

Unstable or positively buoyant air tends to occur when there is strong surface heating by the sun. It rises easily over terrain.

In a stable atmosphere, the air is negatively buoyant, meaning when displaced either up or down it tends to return to its starting height. Stable conditions often occur at night when the air near the surface cools rapidly. It is more easily blocked by terrain and tends to pool in low-lying areas. (Air that is neither stable nor unstable is said to be neutrally stable).

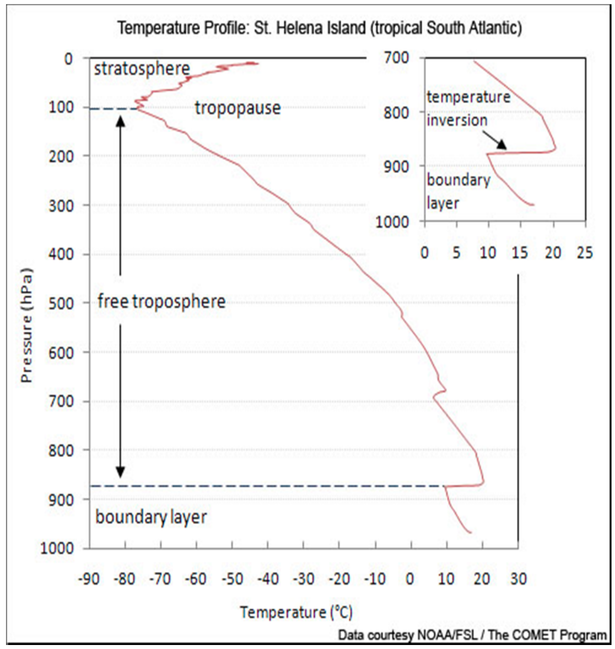

Figure 3-4 Typical air temperature profile in the tropics, showing a temperature inversion, or abrupt increase, at a pressure level of about 875 mb or 1250 m above sea level. (Source: NOAA)

While changes in thermal stability are normally driven by the sun's cycle, both a stable and unstable boundary layer can be created by the movement of air over surfaces of different temperature – for example, from land over water and vice-versa. This is not usually a significant phenomenon in tropical regions, because land and water are close in temperature most of the time. In temperate latitudes, however, large temperature contrasts can arise. For instance, in the local summer, the land may get much hotter than the ocean surface. Air coming onshore will therefore become thermally unstable and rise as it warms. In winter, the opposite process can occur.

The last major influence on winds near the ground is surface vegetation and other elements of land cover, such as houses and other structures. This is often characterised in meteorology by a parameter called the surface roughness length. Because of the friction, or drag, exerted on the lower atmosphere, wind speeds near the ground tend to be lower in areas of higher roughness. Conversely, the relatively low roughness of open water helps explain why wind resources generally improve with distance offshore.

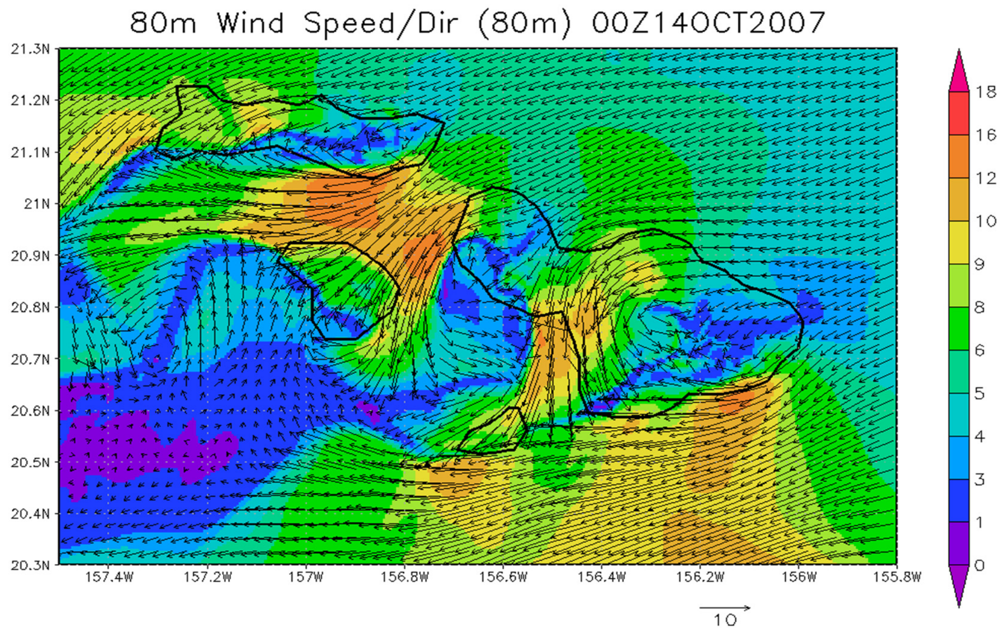

Figure 3-5 Typical wind patterns around the Hawaiian islands of Maui (right), Molokai (upper left), Lanai (lower left), and Kaho' Olawe (smallest). The mountains on both Maui and Molokai block the trade wind, causing a concentration of wind between and around the islands and through the mountain gap in central Maui. (Source: AWS Truepower)

3.4 IMPLICATIONS

It is worth taking a pause here to consider the type of wind climate your island experiences, and the implications for developing a wind project.

If your island is in the tropics or semi-tropics, it is likely you are in a trade wind regime. That means the wind is likely mainly to come from the east (northeast north of the equator, southeast south of the equator), and be fairly steady throughout the year; though if you are close to one of the continental land masses, there may be significant monsoon influence, as well, which can produce a different seasonal and directional pattern. Unless your island has tall mountains – at least 1000 m – the windiest locations are likely to be on ridges running perpendicular to the prevailing wind direction. Open crop or rangeland will be more favourable than closed forest. In the presence of tall mountains, the sides of the mountains and gaps between them may be quite windy, along with the northern and southern extremes of the island. Winds are likely also to be favourable on windward shores (*i.e.* facing into the wind), but will decrease rapidly with distance inland.

The picture is quite different if your island is in the temperate or colder latitudes (above 30°N or 30°S). The wind is likely to be mainly westerly, but with significant components from the south or north depending on the location and time of year. Near continental land masses, the wind may veer along the mainland coast. The cold months are likely to be windier than the warm months, and the winds will rarely be blocked even by high island terrain, making the mountain and ridge tops the windiest locations. However, upwind shorelines may also see good winds.

These general considerations can be refined by talking with meteorologists or atmospheric scientists familiar with your island or region. The research should be well worth your time as it will help you find good sites and interpret the results of your wind measurement campaign.

3.5 POINTS TO REMEMBER

- Familiarity with the main characteristics and driving forces of the wind can be useful for designing and conducting a wind resource measurement campaign.
- Winds are caused by pressure and temperature gradients on scales ranging from thousands of kilometres (global scale) to tens or hundreds of kilometres (mesoscale).
- Islands in the tropics and semi-tropics (within about 30° latitude of the equator) are likely to experience easterly trade winds. Islands in the temperate latitudes (between about 30° and 60° latitude north and south) generally experience westerly winds. In both cases, the wind direction and other characteristics may be affected by nearby large islands and continental land masses.
- The local wind resource can be strongly influenced by the island topography and land cover. For example, winds blowing perpendicular to a ridgeline are likely to accelerate over the top of the ridge. Very tall mountains may block the wind and channel it through gaps, especially in trade wind zones.
- The best wind resources on islands are likely to be found on windward shores and on ridgelines that lie perpendicular to the prevailing wind directions. On tropical and semi-tropical islands with tall mountains, gaps between the mountains, and the islands' northern and southern extremes, may also be windy.
- Further information can be obtained from meteorological texts as well as from meteorologists and atmospheric scientists familiar with the region.

4 CHARACTERISING THE WIND RESOURCE

So far we have reviewed the main factors influencing the wind over a wide range of scales. Now we move on to consider specifically what we mean by the wind resource. How is it defined? What parameters are important to measure or calculate?

A simple definition of the wind resource is that it is the capability of the wind to produce electric power through a wind turbine. If you knew the turbine model ahead of time, then you could express the resource in terms of the annual average power production: "That is a 3000 megawatt-hour site," or "My turbine would produce a capacity factor of 25% at this location" are perfectly acceptable ways to describe the wind resource.

However, it is usually more useful to describe the wind resource in terms that can be applied to estimate the power production of *any* turbine. For that purpose we need to know several things about the atmospheric conditions, including most importantly, the average speed, speed frequency distribution, direction frequency distribution, shear, temperature, air density, and turbulence.

4.1 ANNUAL MEAN WIND SPEED

A rough but handy indicator of the energy production potential at a wind site is the annual mean wind speed at the height of the wind turbine hub (the centre of the rotor). Although it ignores important factors such as the speed frequency distribution and the air density, it is nonetheless used quite often for quickly evaluating and comparing different sites.

What mean speed is necessary for a viable wind project in a particular region depends not only on the wind conditions and turbine characteristics, but also power prices and the availability of subsidies or incentives. Most utility-scale wind projects these days are being developed at sites with an annual mean hub-height speed of at least 6 meters per second (m/s). On many islands, however, competing power sources are very expensive because of the high cost of imported fuel. Thus, it may be possible to develop wind projects at island sites with a lower mean speed than elsewhere. The economic viability of a proposed project must be assessed within the local market context.

In calculating the annual mean hub-height speed from measurements, it is important to adjust for missing data or the unequal occurrence of different seasons in the record to avoid biasing the estimate towards one season. This calculation is described in Chapter 13.

4.2 WIND SPEED FREQUENCY DISTRIBUTION

If the wind always blew at a constant speed, the average speed would be an excellent measure of the wind resource. In reality, the wind fluctuates widely. The speed frequency distribution

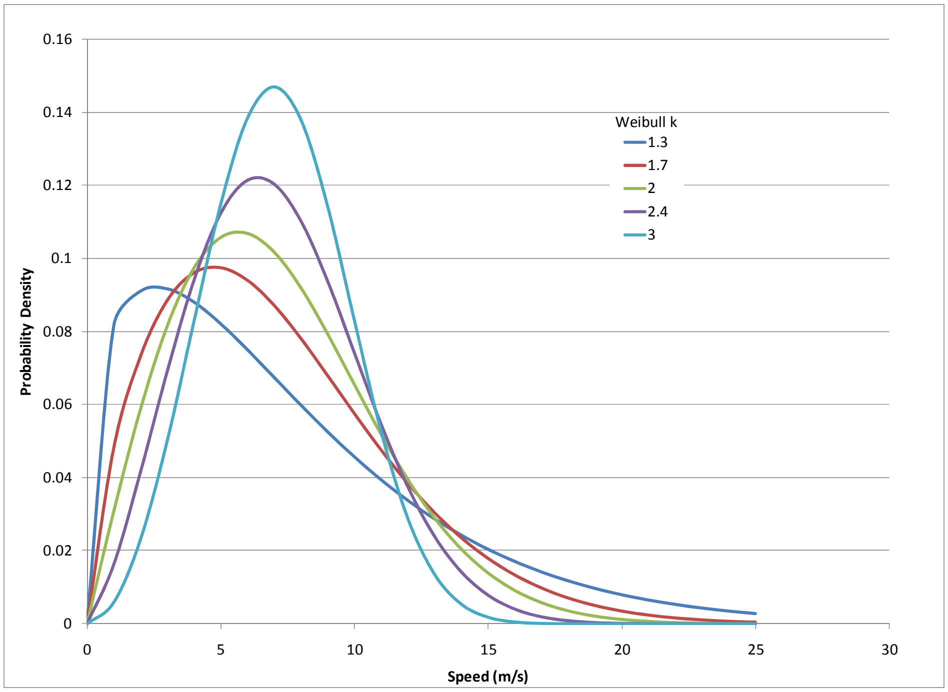

Figure 4-1. Weibull probability density curves for a range of values of *k*. All curves have the same value of *A*: 8.0 m/s. (Source: AWS Truepower)

indicates how often the wind blows at different speeds. A broad distribution indicates a highly variable wind resource; a narrow distribution indicates a steadier one. Since turbines produce much more power at higher speeds than at lower speeds, a variable resource can usually produce more power than a steady one with the same average speed.

The speed distribution is usually presented in reports as a bar chart, or histogram. It is also sometimes summarised as a *Weibull distribution*, which is described by a mathematical formula called the Weibull function.

There are two parameters in the Weibull function. *A*, the scale parameter, has the same units as speed and is proportional to the mean speed of the distribution. *k*, the dimensionless (unit-less) shape parameter, controls the width of the distribution, and is fit to the observations during the calculation process. 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 range of Weibull curves for the same *A* and different *k* is shown in Figure 4-1, while Figure 4-2 presents two examples of a Weibull curve overlaid on the typical histogram plot.

Tropical islands tend to be in the upper end of the typical range (*k* about 3 or more), as trade winds are relatively steady throughout the year. (Actually this is the origin of the word *trade* – a steady path or course that could be followed by sailing ships.) In mid-latitudes, the wind climate tends to be more variable, and *k* is typically around 2 or less. These are rough rules, however, and the wind speed distribution at any particular location may depart significantly from them.

It is often convenient to refer to the Weibull parameters - particularly *k* - when characterising 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 sites fit a Weibull curve quite well, there are some sites where the fit is very poor. Figure 4-2 presents the observed frequency distributions and fitted Weibull curves for two projects in the Hawaiian Islands. The Weibull curve is a good fit at the first project, but not at the second, which has a bimodal (two-peaked) distribution because the site is sheltered from the wind from certain directions.

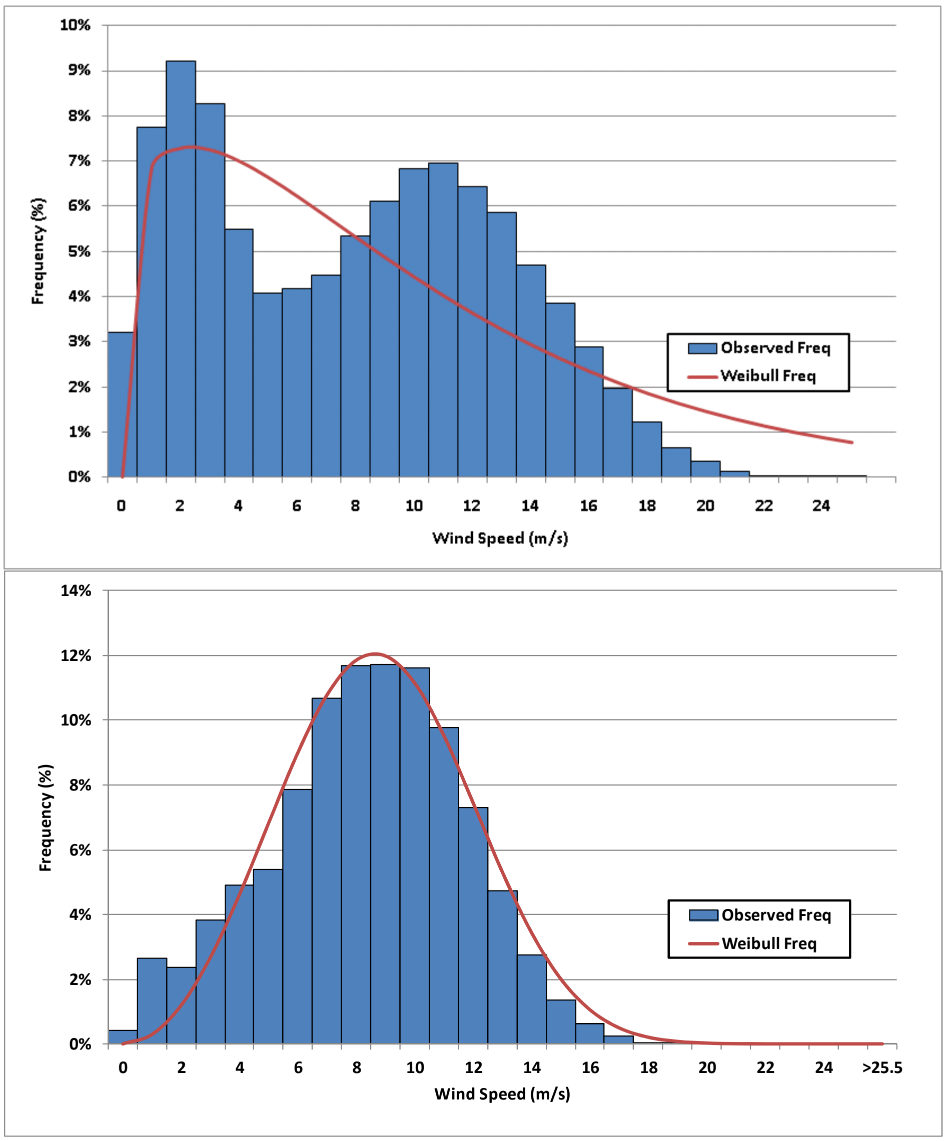

Figure 4-2. Observed speed frequency distributions and fitted Weibull curves. The upper plot illustrates a relatively good fit, the lower plot a relatively poor one. (Source: AWS Truepower)

For this reason, the Weibull parameters should not be used in place of the observed speed frequency distribution when estimating energy production, except in a preliminary way. Many resource analysts choose to ignore it altogether.

4.3 WIND SHEAR

The wind shear is the rate of change in horizontal wind speed with height. It is especially important to know the shear when measuring the wind speed below the turbine hub height, so you can more accurately extrapolate it to hub height. It is also important to identify unusual shear conditions which could affect the performance of a turbine.

The shear at a particular site is determined by several factors, including thermal stability, surface roughness (or land cover), and terrain effects. A stable atmosphere tends to produce high shear, as there is little friction between the different layers of the atmosphere; a neutral or unstable atmosphere tends to have lower shear. High surface roughness (caused by trees, for example) tends to produce high shear, and low surface roughness (open cropland or water) has the opposite effect. Sites that are sheltered by higher terrain often see greater-than-normal shear. Conversely, the shear may be reduced on exposed points on ridge and mountain tops. As with other wind resource characteristics, however, local conditions often depart from these guidelines, and must be confirmed by measurement.

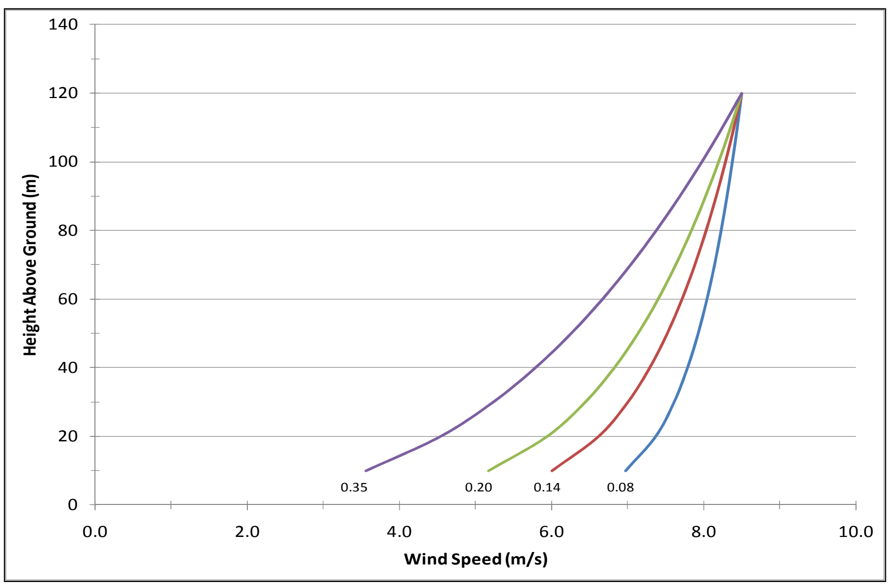

Figure 4-3. Theoretical profiles of wind speed with height for a range of values of the exponent α (0.08, 0.14, 0.20, and 0.35). All curves assume a speed of 8.5 m/s at 120 m height. (Source: AWS Truepower)

There are different ways of characterising shear, but in common practice it is 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:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \qquad \text{Equation 4-1}$$

where:

α = wind shear exponent

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:

$$\alpha = \frac{log\left(\frac{v_2}{v_1}\right)}{log\left(\frac{h_2}{h_1}\right)} \qquad \text{Equation 4-2}$$

where *log* is the logarithm function. Figure 4-3 depicts wind speed profiles for a range of exponents, assuming a speed of 8.5 m/s at 120 m height. For a relatively high shear of 0.35, the mean speed at 40 m height is only 5.4 m/s, whereas for a relatively low shear of 0.08, the mean at 40 m is 7.3 m/s. This demonstrates why, for example, high-roughness areas tend to have a lower mean speed near the ground than low-roughness areas in the same region.

Table 4-1 The typical range of shear exponents observed in different site conditions. (Source: AWS Truepower)

Site Conditions	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 ridge tops, open land cover	0.10 - 0.20

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 4-1 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 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 more often thermally neutral or unstable.

4.4 DIRECTION FREQUENCY DISTRIBUTION (WIND ROSE)

Knowing how often the wind blows from different directions, and with what speed, is important to understanding how the wind resource is distributed over a project area, and how to design the turbine layout. For example, on islands, winds often decrease rapidly with distance from the windward shoreline. Ridges oriented perpendicular to the prevailing wind are likely to offer a better site for a project than other inland locations.

Furthermore, for projects involving more than one turbine, it is important to place the turbines in such a way as to avoid excessive wake losses. (A wake loss is the reduction in wind speed experienced by one turbine due to the energy extracted by other turbines upstream.) In most projects, the spacing between turbines along the principle wind direction is much greater than the spacing perpendicular to it. This configuration maximises the density of wind turbines while keeping wake interference between the turbines, and hence energy losses, manageable.

The wind direction frequency distribution is often presented as a polar plot called a wind rose. Figure 3-9 presents a wind rose showing both the percent of time and percent of energy in each of 16 direction sectors. The energy rose presents a measure of the energy available for conversion in the wind by accounting for the density component of the resource, and can at times (as in the example here) differ significantly from the frequency rose.

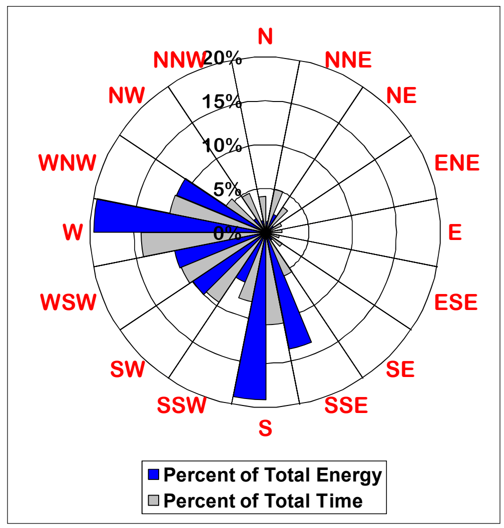

Figure 3-9 Wind rose plot. (Source: AWS)

4.5 AIR TEMPERATURE AND AIR DENSITY

The air temperature at a site is important to know for two main reasons. First, wind turbines cannot operate beyond a certain range of temperatures. Knowing how often the site exceeds the operating temperature range will consequently affect estimates of power production. The operating range is part of the technical specifications of the turbine, which can be obtained from the manufacturer. Temperature limits are not usually a significant factor for islands, however, except in very cold climates.

In addition, and usually more importantly, the air temperature influences the air density, which directly affects a turbine's output. The colder the air, the higher the density and the greater the output at a given speed. Density also depends on air pressure, and hence on elevation above sea level. If the site pressure is measured, the air density can be calculated from the ideal gas law:

$$\rho = \frac{P}{RT} \quad (kg/m^3) \qquad \text{Equation 4-3}$$

where:

ρ = the site air density ($\mathrm{kg/m^3}$)
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:

$$\rho = \left(\frac{P_0}{RT}\right) e^{\left(\frac{-gz}{RT}\right)} \quad (kg/m^3) \qquad \text{Equation 4-4}$$

where:

ρ = the site air density ($\mathbf{kg/m^3}$)
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:

$$\rho = \left(\frac{353.05}{T}\right) e^{-0.03417\frac{z}{T}} \ (kg/m^3) \qquad \text{Equation 4-5}$$

In most tropical island settings, the average air density is around 1.15-1.20 kg/m^3 – somewhat lower than the standard sea-level density of 1.225 kg/m^3 because tropical temperatures are higher than the standard sea-level temperature, 15°C. On a mountain top 1000 m above sea level, the density would be about 1.10 kg/m^3, or around 10%, less, than the standard sea-level. This is a good rule of thumb: every increase of 1000 m in elevation reduces the air density by 10%.

4.6 TURBULENCE INTENSITY

Although it is not one of the primary wind resource indicators, the amount of turbulence, defined as rapid fluctuations in wind speed and direction, can have a significant impact on both turbine performance and wear and tear. The most common measure of turbulence is the standard deviation (σ) of the wind speed calculated from 2-second samples over the 10-minute recording period. Normalising this value with the mean wind speed gives the turbulence intensity (TI):

$$TI = \frac{\sigma}{v} \qquad \text{Equation 4-6}$$

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, or at coastal sites where the wind is coming off the water, to more than 0.20 in forested and steep terrain.

The hub-height 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.

4.7 WIND POWER DENSITY

The wind power density is a measure of the amount of energy available in the wind for conversion by the wind turbine over the cross sectional area swept by the turbine blades. For any given moment in time it can be calculated as follows:

$$WPD = \frac{1}{2}\rho v^3 \qquad \text{Equation 4-7}$$

where ρ is the air density and v^3 the wind speed cubed. Be careful in using this equation, however, as you cannot get the average power density by applying this equation to the average speed cubed. Instead, the power density must be calculated for each time and *then* averaged. This is because above-average wind speeds contribute much more to power than do below-average speeds, thanks to the cubic exponent.

Some experts prefer to express the wind resource in terms of wind power density as it is sensitive both to air density and to the speed frequency distribution, and indicates the amount of energy theoretically available in the wind if 100% of it could be converted to power. A wind power density of 250 W/m^2 roughly corresponds to a 6 m/s site at sea level – the threshold for most utility-scale project development today.

4.8 ESTIMATING TURBINE OUTPUT

Once the wind resource at the site is characterised, the power output of a wind turbine can be estimated. To do this we need one more ingredient: the turbine *power curve* (Figure 4-4). The power curve expresses, for a given air density, the output in kilowatts or megawatts at every hub-height wind speed over its operating range. It is almost always obtained directly from the turbine manufacturer.

All power curves have a *cut-in speed*, where the turbine begins generating power; a *rated speed*, where it reaches its rated capacity; and *cut-out speed*, where its output goes to zero to protect the equipment from high winds.

The calculation of power production can be done either with a time series of wind speed and air density data, or with a speed frequency distribution for the site's average air density. The first is slightly more accurate, but either is acceptable.

The calculation using a frequency distribution is illustrated in Table 4-2. In this example, the power curve is in 1 m/s bins centred on the indicated speed. Thus, the frequency reported in the 3 m/s bin represents the number of hours that wind speeds between 2.5 m/s and 3.5 m/s occur over a year. Dividing the output in kilowatt-hours by the maximum output the turbine could generate if it ran at its rated capacity all the time (rated capacity times 8,760 hours), you obtain the average *capacity factor*. The average annual capacity factor at most sites is between 25% and 50%.

Most turbine manufacturers provide a power curve for a range of air densities. Interpolating the curves to the actual air density for the site is the accepted practice in such cases. On occasion, however, the power curve is available for only one value of air density (such as the standard sea-level density). In that case an adjustment needs to be made.[4] For pitch-regulated turbines (which are the vast majority of large turbines today), this is done by first adjusting the speed in proportion to the cube root of the air density, as in the following equation:

$$v_{adj} = v_{site} \left(\frac{\rho_{site}}{\rho_0}\right)^{\frac{1}{3}} \qquad \text{Equation 4-8}$$

where ρ_{site} is the air density and ρ_0 is the nominal air density for which the power curve is defined. This adjusted speed is then applied to the power curve as usual.

(For stall-regulated turbines, which are the predominant type among small wind turbines designed mainly for residential or farm use, the power can be estimated from the following equation:

$$P_{adj} = P \left(\frac{\rho_{site}}{\rho_0}\right) \qquad \text{Equation 4-9}$$

where P is the turbine output for a given speed at the nominal air density.)

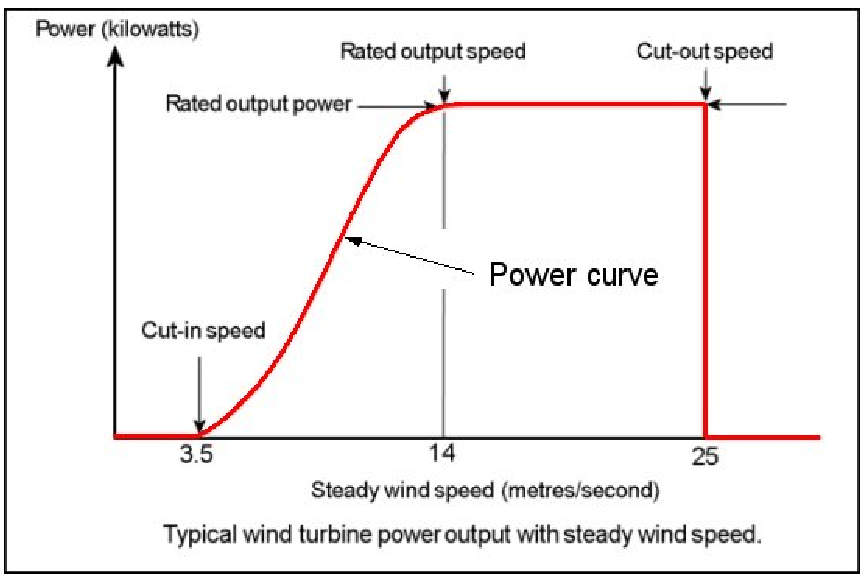

Figure 4-4 Typical power curve for a 1.5 MW turbine at two different air densities.

[4] While the following adjustments are acceptable for making preliminary energy estimates, it is highly recommended that the analyst obtain a certified power curve for a range of air densities from the manufacturer before finalising the project's energy production estimate.

Table 4-2. Illustration of estimating power output using the observed frequency distribution and a turbine power curve for a 1.5 MW (1500 KW) turbine. The capacity factor is the estimated turbine output divided by the output if the turbine ran at full capacity throughout the year. (Source: AWS Truepower)

Wind Speed (m/s)	Frequency (Hours/Year)	Turbine Power (kW)	Turbine Output (kWh)
0	47	0	0
1	133	0	0
2	342	0	0
3	461	0	0
4	461	35	21,532
5	615	115	74,368
6	650	224	170,454
7	841	374	313,956
8	808	577	465,764
9	787	835	657,078
10	748	1101	824,016
11	678	1305	884,715
12	560	1418	793,965
13	451	1466	660,435
14-25	883	1500	1,323,859
Total	**8766**		**6,190,144**
Average Capacity Factor			**47.1%**

These formulas will provide a reasonably good estimate of the gross power production of a turbine (neglecting losses such as electrical losses, wakes, turbine downtime, and others, which are not considered here). However, other wind resource characteristics and environmental factors can impact energy production, and should be considered in an assessment that will be used to finance a project. These include turbulence intensity, wind shear, extremes in wind speed and temperature, and atmospheric icing. Their impacts on energy production are discussed briefly in the following pages.

Turbulence affects wind turbine power production in complicated ways. Most turbine power curves are defined for a mid-range of turbulence intensity at a design speed of 15 m/s, such as

10% to 15%. Turbulence above the design range typically increases power output at low speeds (near the cut-in speed) and decreases it at high speeds (near the rated speed). Conversely, turbulence below the design range typically has the opposite effect.

The impact of wind shear on turbine output is likewise a complicated issue. Most power curves assume a steady, mid-range value of the wind shear exponent, such as 0.20. However, deviations from the nominal output are generally small over a wide range of shear values. Where the impact of shear becomes really important is when the profile changes abruptly – for example, if the shear is high in the lower part of the rotor but low in the upper part.

High winds can result in power production losses if the wind speed exceeds the turbine's design cut-out speed. Additional losses occur because the turbine control software waits until the speed drops below a lower speed threshold (the reset-from-cut-out speed) before allowing the turbine to restart. This is called the high-wind hysteresis loss. Losses of both types can be estimated from a time series of observed wind speeds.

Extreme temperatures, both hot and cold, can result in lost energy because turbines are designed to shut down when temperatures exceed their operating design envelope. As with high speeds, the control software waits until the temperature is within some margin (defined in the turbine technical specifications) of the operating range before allowing the turbine to restart.

Finally, ice accumulation, soil and dust, and dead insects on the turbine blades can result in reduced production due to a decrease in aerodynamic efficiency. Excessive ice accumulation can even cause the turbine to shut down. Icing is of particular concern on islands in cold climates, where moisture-laden ocean air easily freezes on cold surfaces.

4.9 POINTS TO REMEMBER

- The main parameters characterising the wind resource are the mean wind speed, wind speed frequency distribution, wind shear, wind rose (directional frequency distribution), air temperature, air density, and turbulence intensity.

- Of these parameters, the annual mean wind speed is the simplest and most important. Utility-scale wind plants are being developed today with mean wind speeds at hub height of at least 6 m/s. Since competing power sources can often be expensive on islands, it may be possible to develop wind projects at island sites with a lower mean speed than found elsewhere.

- The speed frequency distribution is often approximated by the Weibull function, which has a scale parameter A and shape parameter k. While local conditions vary, most tropical islands have relatively steady winds, with high value of k, and temperate and cold-climate islands have more variable winds, with lower k.

- The power output of a wind turbine is estimated from either a time series of wind speeds or wind speed frequency distribution, the air density and the turbine power curve (energy output at every wind speed). The power curve is usually provided by the turbine manufacturer.

- Besides the mean wind speed and its distribution, the energy production can be impacted by turbulence, wind shear, extreme winds and temperatures, and ice and soil accumulation on the blades.

5 SITE SELECTION

The first step in planning a wind resource measurement campaign is to identify candidate sites where the wind power plants could be developed. The ideal site is one with a good wind resource, enough windy land for a project of the desired size, good access to roads and the electrical system, and few, if any, significant cultural, environmental, or other constraints.

For a large island, it can be helpful to do a preliminary desktop screening using data sources such as topographic and wind resource maps. No matter how effective this screening is, however, it will be necessary to visit the chosen site (or sites) in person to verify conditions, speak with local residents and officials, and assess locations for measurement.

5.1 DEFINING SUITABLE WIND PROJECT SITES

A number of considerations influence whether a site would be attractive for a wind plant. The main ones are:

- Wind resource
- Project size
- Windy land area
- Electrical system access
- Site access and constructability
- Development restrictions

All of these can potentially affect the project in some way, including its size, design, cost, and feasibility.

Wind Resource

Finding a site with a good wind resource is easily the top objective of most developers. What defines "good" depends on the setting, however. Since competing sources of electric power on islands are usually very expensive, the minimum mean hub-height wind speed for a viable project can be lower than for mainland projects. The Fiji wind project, for example, advertises a mean speed at the turbine hub height of only 5.5 m/s, whereas most mainland projects are at sites with mean speeds of at least 6 m/s.

Of course, it is impossible to know the wind resource at a site with precision before the measurement programme is carried out. Local knowledge can be a useful starting point, however. Many windy spots are well known to local inhabitants. For example, one of the best wind project areas in Mexico is in a part of the State of Oaxaca called La Ventosa – Spanish for "the windy place." The Hawaiian language similarly has scores of names for winds belonging to distinct parts of each island. On many islands, local fishermen may be able to advise on coastal winds, and farmers can point to inland areas that are too windy to plant crops without windbreaks.

In addition, two other sources of information can help point towards the most promising sites to be studied: wind resource maps and public wind measurements. They are described below.

Wind Resource Maps

A good wind resource map is one of the most important tools for enabling the analyst to quickly and efficiently screen large areas. In recent years, an increasing number of wind resource maps have been generated by consultants, universities, and other groups using different models and methods.

A leading collection of wind resource maps available on the Internet is the IRENA Global Atlas for Renewable Energy (http://irena.masdar.ac.ae/). It is described as a comprehensive information platform on the potential of renewable energy, which provides resource maps from several sources as well as tools for evaluating the renewable energy potential. With the "Available Renewable Energy Resources" tool, for example, the user can click on the map and obtain estimates of the mean wind speed by month, as well as other resource and energy data, for that point (Figure 5-1). This can provide a helpful preliminary indication of the resource potential.

All wind resource maps should be used with caution, however. None are accepted as the sole basis for investment in utility-scale wind projects, and their accuracy and horizontal resolution (the smallest distance resolved by the model) can vary widely. Some maps are based solely on relatively coarse atmospheric modelling (5 km and greater resolution), without reference to direct wind measurements. They may be helpful for assessing broad areas, but not for selecting specific sites. Others are produced at a high horizontal resolution (smaller than 1 km) and have been validated and adjusted to high-quality wind measurements. They may be useful for identifying windy sites, and in some cases even for making preliminary energy production estimates.

Whatever map you use, it is important to investigate the data sources and methods behind it, and especially to understand the uncertainty in the wind resource estimates. Quoted

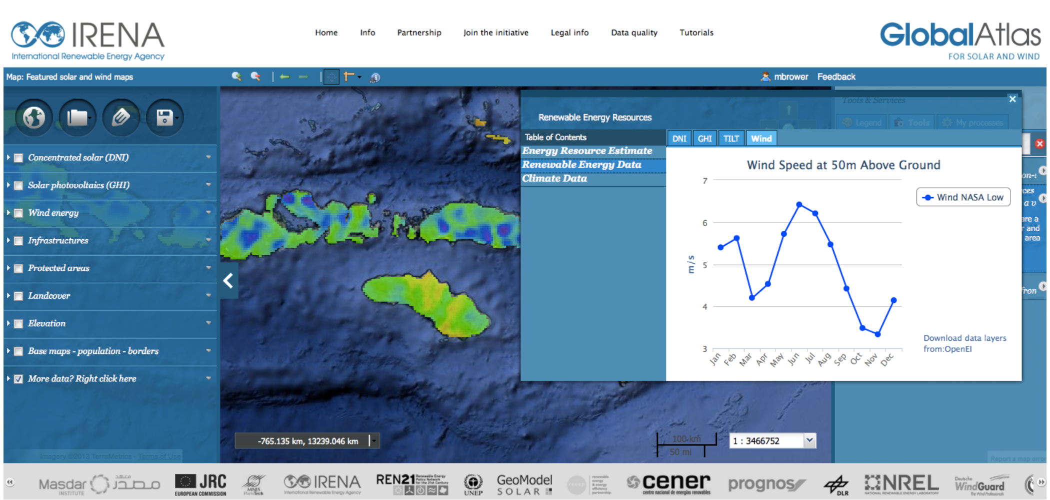

Figure 5-1. The IRENA Global Atlas for Solar and Wind, showing a monthly mean wind speed graph for a point on the island of Sumba, Indonesia.

uncertainties in the mean speed typically fall in the range of 0.5-1.5 m/s. Confidence in the maps is highest in relatively simple terrain and where there is ample validation from high-quality measurements. A greater uncertainty can be expected in complex terrain and data-sparse areas.

Some care is also required to interpret wind 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 and air density, 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.

Public Wind Measurements

Publicly available wind data can be useful 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 ridgeline that runs parallel to a similar ridge under consideration. Tall towers instrumented specifically for wind energy are strongly preferred. Airport and other weather stations can provide a rough indication of the wind resource, but often they are affected by poor data quality, and with their relatively low tower heights (10 m is the international standard) they can easily be sheltered by obstacles such as buildings and trees. Such issues can sometimes be detected by plotting a time series of monthly or annual averages and looking for trends and discontinuities or long periods of missing data.

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
- QC and other adjustments applied to the data

Wind data tend to be more representative of the surrounding area where the terrain is relatively flat and uniform. 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 modelling. 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.

When comparing data from different stations, all wind speeds should be extrapolated to a common reference height (*e.g.* 50 m, a typical island wind turbine hub height). Wind speeds can be adjusted to another height using the power law equation introduced in Chapter 4:

$$v_2 = v_1 \left(\frac{h_2}{h_1}\right)^{\alpha} \qquad \text{Equation 5-1}$$

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.

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, and it is dangerous to offer estimates without detailed study. Nevertheless, some guidance may be helpful if treated with caution. Table 5-1 presents typical ranges of annual mean shear exponent based on our experience in different settings. (As a rule of thumb, an "inland" site is one that is at least 1-3 km from the shore in the prevailing upwind direction.)

Table 5-1 Approximate wind shear exponent ranges on islands. (Source: AWS Truepower)

Site Conditions	Approximate Range of Annual Mean Wind Shear Exponent
Shoreline, open	0.08-0.15
Inland, open	0.12-0.22
Inland, forested	0.20-0.30

For example, suppose you have a set of measurements from a 10 m airport station at an inland site surrounded by many trees and other vegetation. The annual average wind speed from the station is reported to be 4.0 m/s. Assuming a mid-range shear exponent of 0.25 for this inland, forested site, you would project a mean speed at 50 m of $4.0 \times (50/10)^{0.25} = 6.0$ m/s. However, if the same station were on an exposed shoreline (assumed shear exponent of 0.12), the projected 50 m mean wind speed would be $4.0 \times (50/10)^{0.12} = 4.9$ m/s. A reasonable estimate of the uncertainty for these values is 1-2 m/s.

Ideally, data sets should span at least one year to reduce the effect of seasonal variations and should provide consistent data for at least 90 percent of that period. It is best to obtain and analyse the data in their original format, such as a time series of hourly or 10-minute wind speed and wind direction measurements, using methods described in Chapter 12 and Chapter 13. If only a summary is available, it should be used with caution unless the analyst is familiar with the QC procedures and analytical methods used and is confident they were correctly applied.

Project Size

Before starting a site search, it is helpful to have an idea of the size of the wind plant you would like to develop. Many factors, such as project development budgets, island or utility planning targets, and electrical system capacity and capacity growth, can affect this decision.

In relatively small island systems, the maximum size may be set by the peak load (or total generating capacity) of the electrical system the plant will be connected to. This is because wind is a fluctuating resource, and consequently as the proportion of generating capacity supplied by wind grows, the need for load-following reserves and other ancillary services can also increase. Experience and numerous studies have shown that a ratio of wind capacity to peak load of less than around 10% should pose few or no problems on a well-operated grid.

It is important to define the power grid appropriately, however. A large island might have several mini-grids with few or no connections between them. In such a case, it is not the island-wide load that counts, but the load on the mini-grid to which the wind project will be connected. The ability of electrical lines to accept the added wind generation is another important consideration. Many islands depend on medium- and low-voltage distribution lines, and have few, if any, high-voltage transmission lines. Also, many lines may be heavily loaded already, and have little or no spare capacity for a wind plant.

In all cases, the local power company and the relevant governmental or regulatory authorities should be consulted to determine the capacity limits and costs of connecting a new wind project anywhere on the existing system.

The island nation of Fiji provides a case in point. Fiji has three main islands, which together have a peak load of about 138 MW, according to the Fiji Electricity Authority. The three islands comprise four mini-grids. However, about 94% of the generating capacity is on one grid, the Viti Levu Interconnection System on the island of Viti Levu. In 2007 the Fiji Electricity Authority built a 10 MW wind plant on Butoni ridge near the southwest coast of Viti Levu (Figure 5-2). This represents about 7.5% of the Viti Levu grid's peak generating capacity.

In looking for sites and designing a monitoring programme, it is also helpful to have an idea of the size of the turbines that might be employed. Because of limitations in the transportation infrastructure and the need for large cranes to handle the turbine components, most island projects are likely to use smaller turbines with lower hub heights than typical mainland projects. Fiji, again, illustrates the point: the Butoni project consists of 37 Vergnet GEV MP C turbines of 275 KW capacity each. The equivalent-size project in a mainland country would probably employ 5 to 10 turbines of 1.5 to 3 MW each.

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Other issues that could further constrain the wind plant size may appear during the site screening process. These will be touched on below.

Windy Land Area

Aside from a good wind resource, you need enough windy land to support a project of the desired size. The boundaries of the site may be defined by topography – a narrow ridgeline or coastal margin, for example – or by other considerations such as land ownership and control. It is best that the property be contiguous, as isolated (or "stranded") turbines impose a disproportionate cost on a project for both road construction and electrical system cabling.

Judging which parts of an area – such as how far down a slope, or how far back from a shoreline – are likely to be sufficiently windy for turbines is not easy, of course. A wind map can be helpful for guiding such decisions, as long as it is of good quality and sufficiently high resolution. An experienced consultant can also provide advice. But until measurements have been made and a detailed site assessment has been performed, such judgments will necessarily be preliminary. You should expect that they will have to be adjusted later.

Once the approximate boundaries are defined, a rough layout can be developed, and from this a rated capacity for the project. This can be done by following a few basic rules:

- In the axis of the prevailing, or most common, wind direction, place turbines at least 8 to 10 rotor diameters (RD) apart to avoid excessive wake losses. The convention for rotor diameter spacing is from turbine base to turbine base. The Vergnet turbine used in Fiji, for example, has a rotor diameter of 32 m. For this turbine, the minimum spacing would

Figure 5-2 The Butoni wind project on Viti Levu, Fiji. This 10 MW project consisting of thirty-seven 275kW Vergnet turbines illustrates a typical utility-scale project for a large island. (Source: Vergnet.)

be 250 m to 350 m in the downwind direction.

- In the cross-wind direction (perpendicular to the wind), place turbines at least 3 to 5 RD apart.

- If the wind rose has no single prevailing direction, space the turbines at least 6 to 8 RD apart in all directions.

- It may be necessary or prudent to set turbines back some distance from houses and other buildings or neighbouring land parcels that are not part of the project to reduce noise and visual impacts. Local regulations and practice may dictate the setback distance.

For many mainland projects in flat or rolling terrain, employing multi-MW machines, it is typical to achieve a wind capacity density of 5 MW to 10 MW per square kilometre of land area. The density in island environments, with varying terrain and generally smaller turbines and hub height, is likely to be lower. In steep terrain, the turbines are likely to be placed in single strands along the ridgelines perpendicular to the prevailing winds. Plateaus can be ideal for wind projects, as they usually offer stronger winds than the surrounding area, with a wide expanse for placing turbines.

Electrical System Access

After a good wind resource and enough windy land, having access to a nearby electrical line with sufficient capacity to carry the output of the wind plant is vital for a successful project.[5] This is because the costs and risks associated with building new transmission lines are substantial, especially for the relatively small plants likely to be built on islands.

Another factor to consider besides cost is the time and effort required to obtain approval for interconnection. The longer the new line, the more jurisdictions and land parcels it may cross, creating complications for the permitting process. These considerations are best addressed through discussions with the power company, officials with authority over the electrical systems, or an experienced consultant.

Site Access and Constructability

Good road access makes it easier and less expensive to deploy and maintain wind measurement systems, and will probably also reduce the cost of road construction and upgrading when the project is built. The best way to test this is to try to drive to the site. Can you reach it in a 4-wheel drive vehicle? If not, it may be better to find a more accessible site.

Even where roads exist, very steep terrain may preclude the installation of monitoring towers because of a lack of space to lay down the tower components and equipment. It may also make wind project construction and maintenance more costly, and if the wind flow angle is often substantially off horizontal, may increase production losses.

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[5] Here we are considering only centralised, grid-connected wind plants. Distributed or non-grid-connected projects are almost always small, and do not usually merit a wind resource measurement programme.

Working in heavily forested land can increase programme costs, as well, as trees must often be cleared to gain access to potential monitoring locations or to enable tower or turbine installation. Open land, such as cropland and rangeland, usually presents fewer challenges.

Development Restrictions

In selecting potential wind project sites, consideration should be given to potential development restrictions. The fewer such restrictions there are, the quicker and easier the development process is likely to be.

For example, land use restrictions, such as for wildlife protection or military purposes, may limit a site's buildable area. The proximity of turbines to residential areas may also be a concern in some communities. If so, the potential noise and visual impacts may have to be mitigated by requiring that the machines be set back some distance from residences, neighbouring land, or other points of interest.

Exclusion zones due to environmental, cultural, and other concerns should be identified and evaluated early in the site selection process. Such zones can extend beyond officially restricted areas, and although perhaps not ruling out a wind project, can affect the developable area, slow the development process, and increase costs. Some examples include sensitive wildlife habitats not under official protection, locations that are of special historical or religious significance, and sites deemed by the local community to have exceptional scenic or aesthetic value.

5.2 THE SITE-SELECTION PROCESS

The site-selection process typically unfolds in two phases: an initial screening, which is often done remotely, to select a number of candidate sites meeting the criteria described in the previous section; and field visits to confirm site conditions and narrow the choice to the most attractive sites.

Initial Screening

For large islands, it will be helpful to use a Geographical Information System (GIS) to assess the relevant factors in an efficient, systematic manner. Once loaded with the appropriate data layers, the GIS can be queried to identify sites where the mean wind speeds exceed a certain threshold (according to a reliable wind map), are within a certain distance of existing electrical lines, encompass areas large enough to support a wind project of a specified size, and satisfy other criteria. The result of the GIS analysis is typically a list of candidate sites meeting the developer's requirements, which then can be visited and assessed in person.

The most relevant geographic data to incorporate into a GIS for the site screening analyses include the following:

- Wind resource maps
- Topographic data (digital elevation or terrain model)
- Land cover data
- Electrical lines and substations
- Administrative boundaries

- Exclusion areas (national parks, urban areas, etc.)
- Buildings and other structures that may require setbacks
- Roads, railroads, and paths
- Radar and airspace restrictions
- Neighbouring wind projects

Whether these data layers are available and of sufficiently high quality to support the site screening depends on the location. Wikipedia provides a handy list of GIS data sources (http://en.wikipedia.org/wiki/List_of_GIS_data_sources). Local data can often be obtained through government planning agencies and university geography departments.

Field Survey

A field survey should be conducted for all candidate wind project sites. The main goals are to

- Verify the information used in the initial screening;
- Acquire additional information that might influence the site selection (*e.g.* local regulations and community acceptance of wind energy); and
- Assess locations for a wind measurement campaign.

The trip (or trips) should be planned in detail in order to be conducted as efficiently as possible while obtaining all of the required information, and the results should be thoroughly documented.

Verifying Site Conditions

It is important to verify any GIS data and other information used in the initial site screening. While it is impossible to anticipate every problem, here are some general observations on the quality of publicly available data and the need for verification:

- GIS topographic data are usually reliable, but more detailed topographic maps can often be obtained from local or national planning departments, and will be helpful for planning site visits, siting monitoring systems, and designing project layouts.
- Land cover classifications, whatever their source, are often outdated or wrong – forest may be labelled as cropland, or vice-versa, and residential areas may be overlooked entirely, to cite some common problems. A spot check in the field should quickly determine if such errors are widespread. Aerial photographs (such as those available in Google Earth) can also be helpful.
- Maps of electrical system infrastructure, such as transmission and distribution lines and substations, are often impossible to obtain, and where available they may be schematic rather than detailed. Here, the best course is often simply to drive around looking for lines, taking photographs of transmission poles and their ancillary equipment, and marking them on a map or GIS. A representative of the local power company may be able to confirm the voltage, number of circuits, and substation locations, and discuss interconnection options where required.
- While primary roads are usually fairly accurately rendered, many secondary roads are not shown on GIS and other maps, and their condition is unknown. Aerial photographs can

help flag gaps and errors, but there is no substitute for driving the roads throughout the area.

Additional Information

One of the chief reasons to visit a proposed wind project site is that it offers the opportunity to become acquainted with local residents, landowners, community leaders, and representatives of government agencies, among others, and to explain to them your goals and plans and how the project will benefit the community. These dialogues will help raise public awareness of the proposed monitoring effort, gauge the public and official reaction, and address any initial questions or concerns that may arise. Such early outreach – valuable for any wind project – is all the more important on islands where wind energy projects and resource assessment programmes are new.

A specific goal is to obtain information about local regulations governing wind monitoring and wind energy projects. Permitting requirements vary from country to country and even between jurisdictions, so it is important to have local knowledge to plan ahead and prevent any significant delays in the monitoring programme. Are there limits on the height of towers? Are there setbacks that must be respected for tall towers? Are special permits required to install towers or other measurement systems? Situations that may trigger the need for a permit include proximity to an airport or to sites of cultural, environmental, historical, or religious significance. Other regulations may include the need for certification of the tower design by a qualified engineer.

Assessing Locations for Wind Measurements

Identifying and evaluating potential locations for wind measurement systems sets the stage for planning the measurement campaign. It is also a test of the suitability of the site for the proposed wind project. If it is difficult to find or access good locations for a measurement system within the project area, it may also be challenging to build a wind plant there.

The factors to be considered in assessing locations for both measurement systems and wind turbines include slopes, soil types, and vehicle access. In addition, for turbines, constructability is a concern. There should be sufficiently flat and open areas (or areas that could be cleared and levelled) for turbine components such as blades and tower segments to be laid down before being lifted into place. Consideration should also be given to the need to bring heavy equipment to the site. Identification of existing roads requiring improvement and proposed turbine spacing can also be evaluated, in at least a preliminary way, to assess the feasibility of constructing a wind farm of the desired size.

Another important consideration – especially for islands prone to severe storms - is the survivability of the equipment. Does extra space need to be allotted for the towers or turbines to be tilted down or dismantled ahead of an approaching storm? Is extra equipment (and its associated storage space) necessary and readily available? Are the soil conditions sufficiently stable to anchor a tower or turbine under high loads? Such concerns should be addressed early in the site and turbine selection process, and clearly communicated to all relevant parties.

More guidance on assessing sites for measurement towers is provided in Chapter 6.

Documentation

Full and detailed documentation of the field survey phase is essential for planning and carrying out the subsequent wind measurement campaign. The documentation provides the basis on which any decision to proceed to installing wind measurement systems will be made, and therefore it should be available for review by stakeholders (managers, investors, lenders, and others). The documentation also supports the final decision on which location (or locations) within the proposed project area will be monitored, and flags issues that may need to be addressed before measurement equipment can be installed.

At a minimum, the following information should be recorded:

- Central latitude and longitude of the site;
- Topographic or similar map showing the proposed site boundaries, land parcels, and other relevant boundaries;
- Locations and routes of observed electrical lines and roads;
- Photographs of the site from several vantage points (marked by a global positioning system (GPS) device), showing key features and typical land cover and topography;
- List of candidate locations for wind measurement, with assessment of each including access, obstructions, representativeness of wind conditions, and the likely difficulty of securing rights to the property;
- Synopsis of local regulations affecting wind measurement systems and wind projects;
- Summaries of conversations with local landowners, community leaders, government representatives, signalling general level of community support and concerns to be addressed; and
- Any other information that may be relevant to the decision to proceed with a wind measurement campaign or to the programme design.

5.3 POINTS TO REMEMBER

- In addition to a good wind resource, an attractive site should contain adequate windy land area, be close to transmission and roads, and be relatively free of restrictions.
- Although available regional wind resource maps are useful for obtaining a preliminary indication of a site's wind resource potential, on-site data are necessary to develop a more accurate estimate of the long-term wind speed and energy potential.
- Knowledge of the size of the proposed wind plant will help determine the amount of land area required for development and assist in constructing preliminary wind turbine layouts.
- Geographical Information Systems (GIS) can be used to screen large areas to identify candidate wind sites that satisfy a list of siting criteria.
- Field surveys should be conducted to candidate sites to verify on-site conditions, gather local information that may have a bearing on the wind project, and select monitoring locations.

6 DESIGNING THE MEASUREMENT CAMPAIGN

The design of the wind measurement programme can begin once the project site (or sites) has been selected. The design process includes determining the number of measurement systems, their general type (*e.g.* tower or remote sensing), and their placement within the proposed project area. The expected duration of the measurement programme is also established at this stage, along with a budget or budget range. This chapter provides guidance on the overall process. Details of the sensor selection and system configuration are addressed in subsequent chapters.

6.1 NUMBER OF MEASUREMENT SYSTEMS

A key driver of the overall programme budget and scope is the number of measurement systems. The recommended number for a particular site is driven by two main factors: the size of the area potentially occupied by turbines and the terrain complexity. While there is no set industry standard, the guidelines provided in Table 6-1 provide a starting point for sizing the monitoring programme. The distances in the table are the maximum from any turbine to the nearest measurement station. (Here is another place where the rough layout developed in Chapter 5 will come in handy.)

Table 6-1. Recommended maximum spacing between turbines and monitoring systems

Project Site	Terrain	Maximum recommended distance between any proposed turbine and nearest measurement
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

*Complex terrain refers to any site where terrain effects on the meteorological measurements may be significant.

The reason the maximum distance depends on the terrain type is that more complex terrain (or land cover) generally results in more variation in the wind resource. To keep the wind resource uncertainty as low as possible, more measurement systems are needed to characterise the variation.

How do the numbers work out in practice? Consider the example of a single line of turbines along a ridgeline or shoreline aligned roughly perpendicular with the prevailing wind direction. The turbine has a rated capacity of 250 kW and a rotor diameter of 30 m, and following the guidelines in Chapter 5, the turbines are spaced roughly 120 m, or 4 RD, apart. So 8 turbines can fit on an axis 1 km long. The terrain is moderately complex, so according to Table 6-1, the maximum distance from any turbine to the nearest measurement system should be about 5 km. Thus, one centrally located measurement system will suffice to cover a line 10 km long containing about 80 turbines: a 20 MW project. Beyond this limit, a second system should be added up to a maximum of 40 MW, then a third, and so on.

As you can see, for most island projects, according to these guidelines, a single measurement system should suffice. This conclusion should be treated with caution, however. There are many situations where it would be prudent to install additional systems. For example, for a project that spans two ridges with very different elevations, exposure, or orientation with respect to the prevailing wind, it would be reasonable to place a system on each ridge, even if the guidelines call for only one. The same applies if the turbines are to be placed at different distances from a shoreline. When in doubt, consult an expert.

When more than one measurement system is deployed, it is recommended that one system (usually a tall tower) be designated the primary system, and be maintained at the site for the duration of the measurement programme to serve as a reference. This provides a point of comparison for the secondary systems and allows them to be adjusted to the same reference period, which can help reduce the uncertainty in the wind resource and energy production. The secondary systems will be used to monitor the wind conditions at other locations within each project area. Depending on the results, they may be relocated after the first full year of data collection.

6.2 CHOOSING LOCATIONS FOR MEASUREMENT SYSTEMS

When deciding where to put measurement systems, three guiding principles should be followed. First, the wind conditions at the locations should be representative of those likely to be experienced by the turbines. Second, the measurement locations should be readily accessible for installation and maintenance. And third, the wind measurements should not be strongly affected by obstacles. Each of these points is addressed below.

Measuring Representative Wind Conditions

If only one measurement system is planned, then it should be in a representative, and usually central, location within the project area. This minimises the uncertainty in the wind resource for the whole project. *Avoid the temptation to measure at the very best location* – the highest terrain or the closest point to the shore, for example.

With two or more monitoring stations, a diversity of locations, each representing the resource likely to be experienced by a subset of turbines, should be chosen. The more stations, and the more the resource measurement campaign captures the full range of conditions experienced by the turbines, the smaller the uncertainty in the expected energy production.

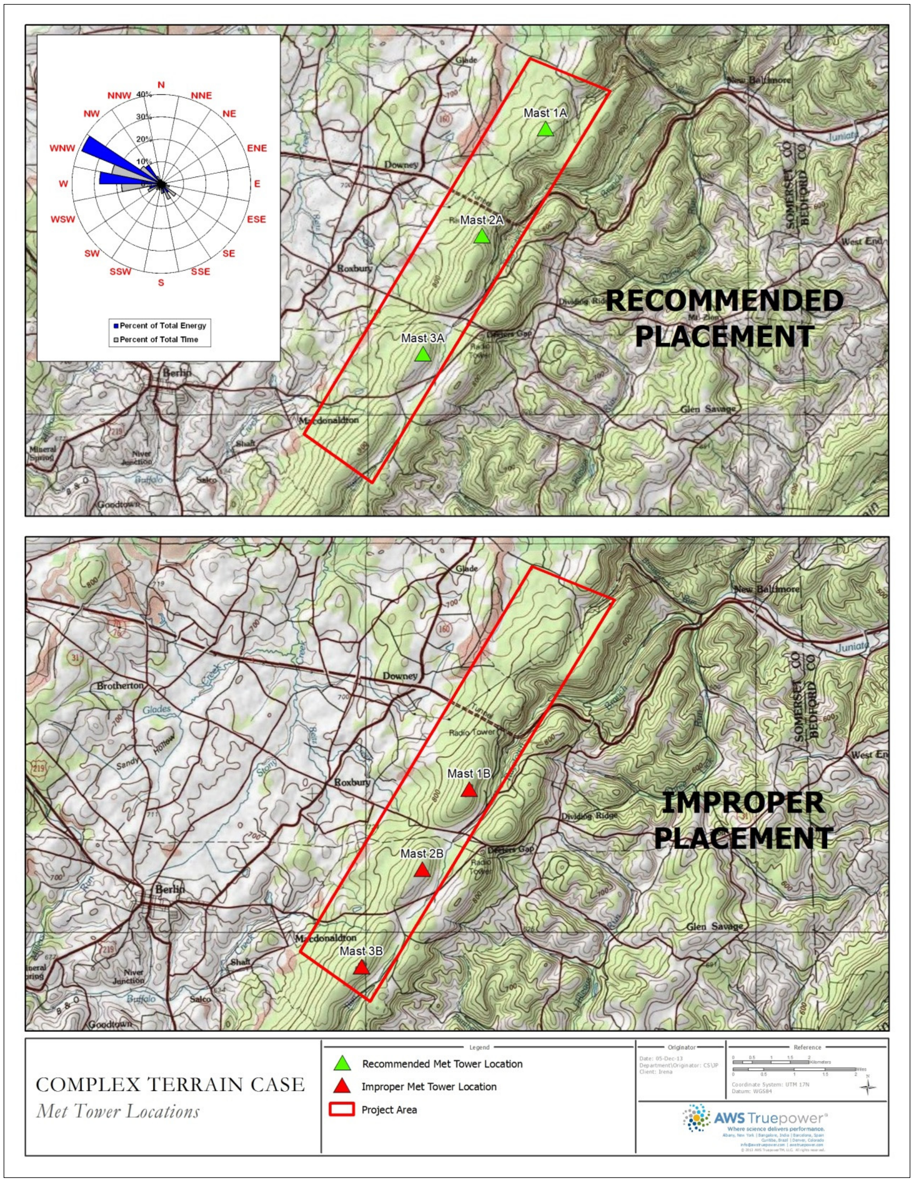

Figure 6-1. Measurement system siting – complex terrain case

Distributing the measurement systems more or less evenly among the turbines in the preliminary layout is one way to try to capture a diversity of wind conditions. Another is to make sure you cover a range of elevations, ridgeline orientation, or distance from shoreline – whichever factors appear likely to drive variations in the wind resource over the project area. This is sometimes hard to judge, and expert advice can be helpful. As a general rule, though, variations in elevation, exposure (*i.e.* elevation relative to upwind or downwind terrain), land cover, and (for coastal sites) distance to shore, are key drivers.

Figure 6.1 and Figure 6-2 illustrate some "dos" and "don'ts" of system placement. The first figure shows a ridge in complex terrain, the second a coastal site. The red rectangle on each map represents the limits of the project area where turbines are likely to be placed. The upper map shows the recommended placement of 3 measurement towers within each area (green rectangles); the bottom map shows a sub-optimal arrangement of the same 3 towers (red rectangles).

In Figure 6.1 each tower in the sub-optimal programme design (bottom map) is located on a high point on the ridge, including the highest elevation (Mast #3B). Because of their elevation and exposure, the wind resource at these locations is likely to be better than average for the rest of the ridgeline. This could bias the wind resource and energy production estimates for the whole project. Also, since the towers are at the same elevation, they provide no information regarding

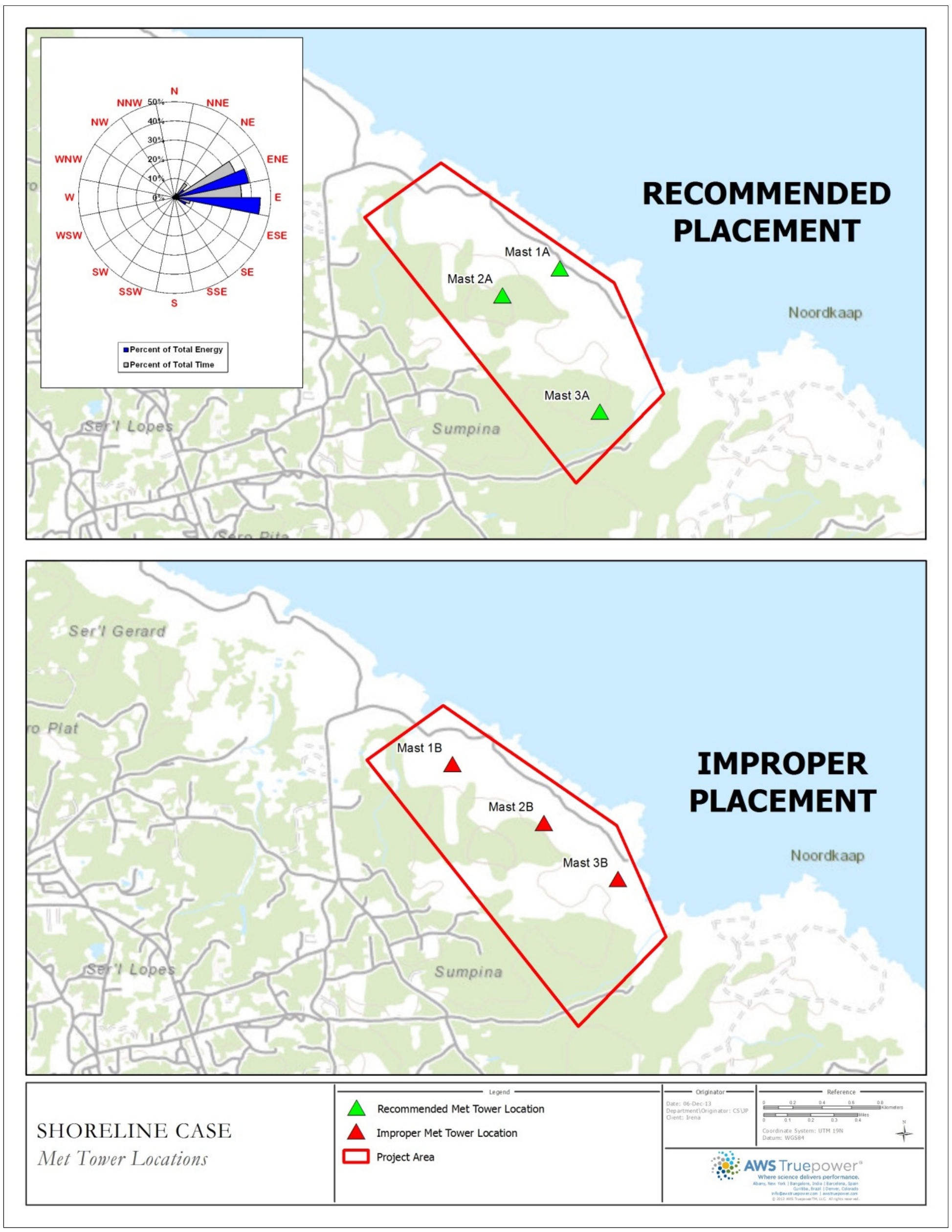

Figure 6-2. Measurement system siting - shoreline case

the variation in mean wind speed with elevation. Thus it is difficult to estimate the resource for turbines that are off the main ridgeline. Finally, the towers are all in the lower half of the project area.

In the recommended scenario (top map) the towers are more evenly distributed in the project area and capture a wider range of elevations and wind resources likely to be experienced by the turbines.

In Figure 6-2, the three towers in the sub-optimal case (bottom map) are well distributed along the shoreline but are all at the same distance from the shore. Thus, they provide no information about how quickly the wind resource may decrease with distance inland – an important parameter in designing this project and estimating its energy production. The towers in the recommended scenario correct this deficiency.

Site Accessibility

On many islands, finding suitable monitoring locations that are easily accessed by truck or 4-wheel-drive vehicle can be a significant challenge. Especially steep terrain and dense vegetation can make installation, data collection, and equipment maintenance difficult or impossible. Keep in mind that weather conditions can affect site access, as well. The rainy season can make dirt roads impassable. Conversely, dry spells can create a fire hazard and prevent staff from approaching the site. Local residents and weather records should be consulted to assess these risks.

The accessibility of sites can shape not only the placement of measurement systems but the type and maintenance strategy employed, as well. For example, shorter towers may be needed because of limited clearing space. It may be necessary to put measurement systems on existing roads, trails, or clearings, even if they are not in an optimal location for resource assessment. Site-specific solutions can often be developed for any one or number of issues, but they can be costly and may take a substantial amount of time to implement.

On islands prone to hurricanes or typhoons, it may be necessary to dismantle or remove equipment ahead of approaching storms. Where severe weather occurs often, plans should be put in place in advance to mobilise staff and resources to respond quickly to storm warnings. Where warnings are insufficient, the site is hard to access, or options to protect equipment are limited, you may have to let the measurement systems weather the storm and inspect or repair them after the fact.

Obstructions

Towers or remote sensing systems should be sited well away from obstructions such as isolated stands of trees, buildings, and rock outcroppings that might affect the accuracy of the wind measurements. What this means in practice depends on the size of the obstruction and the height of the measurements. Figure 6-3 illustrates the general effects of an obstruction on wind speed and turbulence. The zone of influence extends roughly up to 2 times the obstacle height in the upwind direction, 10 to 20 times the obstacle height in the downwind direction, and 2 to 3 times the obstacle height in the vertical direction. As a rule, if sensors must be placed near an obstruction, they should be outside these zones of influence.

When placing a wind monitoring system near or within a forest, extensive tree stand, or other obstacle, it is important to consider whether the location is typical of where turbines are likely to be installed. 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.

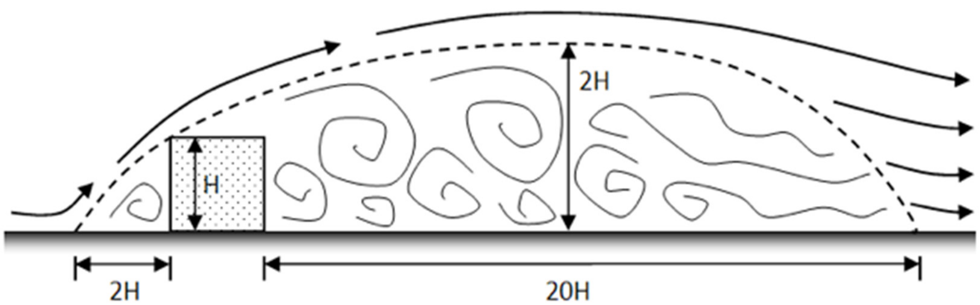

Figure 6-3 Obstruction effects on airflow.

6.3 CHOOSING MEASUREMENT SYSTEMS

With the project or projects defined and candidate measurement locations selected, attention turns to choosing a measurement system. Two basic types are available today. The first and still by far the most common is a tall tower equipped with meteorological instruments of various kinds. The second, which is growing in popularity, is ground-based remote sensing – either sodar (sound detection and ranging) or lidar (light detection and ranging). Towers and remote-sensing systems are covered in detail in Chapters 7 and 8, respectively.

Tall Towers

Tall towers[6] have traditionally been the mainstay of wind resource measurement, and they will probably continue to be so for island projects. One reason is that the towers and their equipment are a familiar and widely available technology, and the skills required to install and maintain them can be quickly acquired. In addition, towers below 100 m in height are relatively inexpensive, and lattice versions can often be manufactured locally. Consequently, for island projects employing just one measurement system, you cannot go wrong choosing a tall tower.

Using Existing Towers

At first glance, existing multi-use tall towers (such as communications towers) appear to be an appealing option for wind resource monitoring. Since no new structure is required, the permitting process has been completed, and on-site power is usually already available, they may offer a timely and cost-effective alternative to a new, dedicated tower. However, such "towers of opportunity" often have significant drawbacks, and consequently they are much less frequently

[6] There is no accepted convention defining what "tall" means, but anywhere from 30 m to 80 m height is common, and some are taller than 100 m. For reasons discussed in the previous chapter, island projects are likely to use shorter towers – from 30 m to 60 m.

used for resource assessment than dedicated measurement systems. Important points to consider when evaluating an existing tall tower for a wind monitoring programme include the following:

- The tower may not be in an optimal location for accurate resource measurement.
- Multi-use towers are often large structures with other equipment such as antennas that can distort wind speed readings.
- The weight and positioning of existing equipment can put constraints on the number and placement of new sensors for resource assessment.
- Gaining access to the tower and wind monitoring equipment to perform routine maintenance or replace malfunctioning sensors may require advance notice to the tower owner, which could result in delays in equipment repair leading to lost data.

Where one or more of these concerns exists, it may not be worth the money and effort needed to equip an existing tower for resource measurement.

Remote Sensing Devices

Remote-sensing systems have several appealing characteristics, especially for large wind projects or ones using large turbines. One is that they can measure winds well above the heights reached by most towers. This avoids the need to extrapolate the wind speed up to the hub height and across the full range of heights spanned by a turbine's blades, thus potentially allowing for a more accurate estimate of energy production. Information on turbulence, vertical motions, and directional shear (veer) across the rotor plane - all of which can affect turbine performance - can also be obtained.

Another attractive characteristic of remote-sensing systems is that they can be deployed and moved relatively easily by a small crew, and sometimes to places where it would be difficult or impossible to install a tall tower. Used in this fashion, they complement towers and provide a spot check of the resource at different locations across the project area. Most remote sensing campaigns last several weeks to a few months. Increasingly, however, sodar or lidar systems are being used for extended measurement campaigns in an effort to better characterise the annual wind resource.

At the same time, the disadvantages of both sodar and lidar are significant in many island settings, especially those far from sales and service centres. Not only do the systems (especially lidars) cost much more than tall towers of the size likely to be used on islands, they require more expertise to set up and operate, which may not be available (or may be expensive to obtain) in remote locations. They also require more robust power supplies.

The acceptance of sodar and lidar measurements by financial institutions is a significant concern, as well. As remote sensing devices are still fairly new on the scene, many banks and investors hesitate to rely on them as the sole source of resource data for estimating energy production – although acceptance is growing. Such issues should be carefully weighed before deciding to invest in such a system for an island measurement campaign.

Further information on remote sensing systems is presented in Chapter 8.

6.4 SITE ACCESS AND LAND CONTROL

Once far enough along in the planning, the developer[7] typically negotiates a lease or other arrangement with landowners to allow installation and operation of the wind measurement equipment. The agreement usually serves to secure an option for the land should the wind energy project go forward. Ideally, the agreement should extend over all the land that might be used for wind turbines. This ensures that if the monitoring programme is successful, the developer will be able to control the land that is needed for the plant to be built. It also keeps other developers from competing for the same space.

In addition to leases, other land control instruments can be utilised as well, such as rights-of-way or land easements. All such arrangements accomplish the same goals, but sometimes existing legal frameworks can favour one approach over another. An option period typically lasts three to five years to allow sufficient time to evaluate the wind resource. Before the term is over, the developer has the choice of either exercising the option to lease the land for the 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 lease it for a long period if 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/controlled: 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.

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[7] This section applies mainly to land-lease agreements negotiated by private developers. Agreements entered by other entities conducting resource measurement campaigns – such as government agencies, power companies, and non-profit organisations – may have similar elements, but usually avoid a project option.

- Crop protection: Typical lease provisions require developers to use their best efforts to minimise 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 and 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.

6.5 COST ESTIMATION

The process of designing a wind measurement campaign often involves trade-offs between cost, convenience, and performance. At this early stage of project development, budgets can be tight, leading to a desire to economise on equipment selection and installation costs. However, while cost is an important consideration at all times, a monitoring programme that is designed with cost as its paramount concern may be unsuccessful.

It is difficult to estimate the costs of a wind resource measurement programme in advance, as they will vary greatly by location depending on many factors, including labour costs, the availability of local installation and maintenance crews, transportation costs, and taxes or import duties.

As a general matter, the monitoring cost can be divided into three main categories: labour, equipment, and other.

Labour: Table 6-2 lists the main tasks to be accounted for when budgeting for labour. Some tasks require just one person; others – especially those that deal with equipment installation and maintenance on tall towers – may require a team of four or five.

Equipment: Equipment costs can be 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.

Other expenses: Other expenses may 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, as well, depending on the number and duration of calls and the rates.

Table 6-2 Labour tasks to account for in a measurement programme budget.
(Source: AWS Truepower)

Administration	
•	Programme 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

Economies of scale can be achieved with multiple towers, or when coupling a tower and remote sensing system, particularly when installed at the same location. 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. Most of the savings are in labour, since staff time and travel can be used more efficiently. Travel expenses can be reduced if more than one site is visited in a single field trip. Savings on equipment can be realised through vendor discounts and by sharing installation equipment (*e.g.* gin pole, winch kit) among sites.

Price quotes for equipment packages meeting the programme's objectives should always be obtained during the planning process, along with information on warranties, product support, and delivery dates, and compared between suppliers. A manufacturer that provides comprehensive product support can be an 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 Chapter 9.

6.6 POINTS TO REMEMBER

- The number of measurement systems needed at a particular site depends on the size of the area potentially occupied by turbines and the terrain complexity. More systems are required in complex terrain where the wind resource is more variable.
- Measurement systems should be positioned in areas likely to be representative of the future turbine locations and not in areas where the wind resource is expected to be best.
- It is important to take into consideration the accessibility of sites when selecting locations to monitor the wind resource.
- Measurement systems should be placed well away from obstructions so that their impact on the recorded data is minimised.
- A tall tower equipped with meteorological instruments is the most common measurement system in use today, but remote sensing systems, such as sodar (sound detection and ranging) and lidar (light detection and ranging), are gaining in popularity.
- Lease agreements between the developer and landowner allow the installation and operation of the wind measurement equipment and usually also serve to secure an option for the land should the wind energy project go forward.
- The costs associated with a monitoring campaign, including labour, equipment, and other expenses, are often difficult to pinpoint in advance and will vary by location. Economies of scale can be realised when installing multiple measurement systems.

7 INSTRUMENTED TALL TOWERS

One of the most critical steps in the implementation of a wind resource assessment programme is the selection and configuration of the monitoring equipment. The choices made at this stage have implications for the quality, quantity, and cost of the data collected, all of which can influence the future development steps and priorities.

This chapter deals with instrumented tall towers, which have traditionally formed the backbone of most wind resource assessment programmes. (See Chapter 8 for remote-sensing systems.) It describes the types of tall towers and wind resource monitoring equipment, provides recommendations on equipment configuration, and addresses data storage and transfer, power supply, and other considerations that are crucial to successful campaign design.

7.1 TOWER SELECTION

There are two basic tower types: tubular and lattice. For both, three versions are available: tilt-up, telescoping, and fixed. Most utilise guy cables to stabilise the tower. Exceptions are self-supporting lattice and monopole towers. Each type of tower has characteristic advantages and disadvantages, which should be weighed in deciding which to use in a wind measurement programme.

Whatever their type, towers must 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. Some communities have their own design requirements for wind and ice loading that can have implications for the permitting process. In coastal and island environments, resistance to salt-water exposure is important. When in doubt, seek expert advice to determine if a particular tower design is adequate.

Tubular Tilt-Up Towers

Tubular tilt-up towers are probably the most widely used type for wind resource measurement in mainland wind energy markets. This is mainly because they are relatively inexpensive and provide many options for configuring and mounting sensors. Tubular tilt-up towers come in sections but are assembled on the ground and then lifted into place. Towers designed for wind energy come in heights ranging from around 30 m to 80 m. For most island wind resource campaigns, a height of 40 m to 60 m is likely to be adequate.

Though popular, tubular tilt-up towers have some limitations. Erecting the towers is much easier if the terrain is relatively flat and free of trees. On sloping or uneven ground, the guy wires may have to be adjusted often as the tower is raised, requiring a more experienced crew. If the tower is placed in a wooded area, a clearing must be created around the tower large enough to lay it down and anchor the guy wires. Tubular towers can require a crew of four or more to install; if the crew is experienced, however, a smaller number may suffice.

Figure 7-1. A 34 m tubular tilt-up tower. (Source: NRG Systems)

Lattice Towers

Lattice towers built specifically for wind measurement are the standard when very tall towers (above 80 m) are required. On islands, they may also be the best choice at lower heights. One reason is that they can often be manufactured locally, as the skills and infrastructure are similar to those required for manufacturing radio and cellular telephone towers. This can reduce costs and import duties, as well as support the local economy. Also, while the size of the crew needed to install a lattice tower may be comparable to that required for a tubular tower, the number needed for maintenance is usually smaller. This is because a single person can climb a lattice tower to service the equipment, whereas a crew is needed to raise and lower a tilt-up tubular tower. (Further information on tower installation and servicing is provided in Chapter 9.)

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 can be assembled with the tower lying on the ground, and then picked up as a unit and put in place with a crane, or they can be stacked in place using a winch and jib pole system.

On a guyed tower, cables are attached at one or more heights and in three or four directions to stabilise the structure. A self-supporting tower broadens near the base to support the structure above it. It usually has three legs with a solid footing, such as a concrete pier, under each. Despite their larger footprint, guyed towers are more widely used than self-supporting towers for wind resource measurement because they are lighter and consequently less expensive.

Figure 7-2 A guyed lattice tower instrumented for wind monitoring. (Source: AWS Truepower)

Existing Lattice Towers

As we saw in Chapter 4, making use of existing towers (such as communications towers) for wind resource measurement can be attractive, but the possible drawbacks need to be considered. This is especially true when it comes to mounting and configuring sensors. Since such towers come in a wide range of sizes and lattice designs, the sensor mounting hardware must often be custom-designed and custom-fabricated. To minimise the effect of especially wide lattice towers on speed measurements, much longer and heavier mounting booms than usual may be required. Existing equipment such as radio antennas may restrict the places where new sensors can be placed to avoid excessive wind flow disturbance. Possible electromagnetic interference from existing tower equipment must also be considered.

All such design needs must be determined during the initial site investigation; this is not a "day-of-installation" task. Note that adding support booms for anemometers and other instruments can create wind or ice loads exceeding the tower's design specifications. Where there is any doubt, the implications of adding equipment to an existing tower should be reviewed by a qualified engineer.

7.2 INSTRUMENT SELECTION

Three parameters form the foundation of the site resource assessment and are recommended for any monitoring campaign: horizontal wind speed, wind direction, and air temperature. Table 7-1 lists the nominal specifications for these respective sensor types meeting the standards of wind resource assessment. In the following sections we describe the most common equipment types.

Table 7-1. Specifications for standard sensors. N/A = not applicable. (Source: AWS Truepower)

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%	≤ 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

Horizontal Wind Speed

Horizontal wind speed is the most important indicator of a site's wind resource. For this reason, close attention should be paid to choosing appropriate anemometers for your project.

Three general anemometer types are available for measuring horizontal wind speed:

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

- Propeller Anemometer: This instrument consists of a propeller (or prop) mounted on a horizontal shaft which 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 tends to 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. Propeller anemometers are sometimes favoured in icing-prone climates due to their greater resistance to icing.

Cup Anemometer
(Wind Sensor)

Prop-vane
(R.M. Young)

Sonic Anemometer
(Campbell Scientific)

- 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. The geometry can be set up to measure the wind in two or three dimensions; the latter allows the measurement of vertical winds. 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, however, and may require significantly more power.

Of these, the cup anemometer is by far the most popular because of its relatively low cost and generally good accuracy, and is the default choice for island wind resource campaigns. However, both propeller and sonic anemometers can be used.

There are many industry-accepted cup anemometers. A list is provided in Chapter 9. Although each of these sensor models meets wind-industry standards, it may be desirable to deploy more than one model on a tower. This strategy aims to find an optimal combination of anemometer attributes, and can also reduce the risk of data losses or measurement errors caused by problems affecting just one model.

Several issues should be considered in choosing the right combination of instruments for your project.

Accuracy. Some anemometers have been classified according to the standards outlined by institutions like MEASNET or the International Electrotechnical Commission (IEC).[8] The performance of these anemometers, which are referred to as *IEC Class I*, complies with specifications for high-accuracy applications such as power curve testing. Class I anemometers are generally more expensive than standard instruments, however. A good compromise is to pair a Class I anemometer such as the WindSensor P2546A or the Vector A100LK with a less expensive model such as the NRG #40C, at one or more heights on the tower.

Response to turbulence. Another distinguishing characteristic of cup anemometers is their *distance constant*. This is a measure of how quickly an anemometer responds to an abrupt change in wind speed. A smaller distance constant is preferred in highly turbulent environments, as otherwise the anemometer tends to "overspeed", *i.e.* read too high. All cup anemometers are prone to overspeeding, but those with a large distance constant overspeed more. Anemometers commonly used for resource assessment have distance constants ranging from 2.1 m to 3.0 m.

Response to vertical winds. In relatively steep terrain, the wind often has a significant vertical component. Since turbines respond only to the horizontal wind, it is important in such conditions to measure only the horizontal component. Class I anemometers are generally better in this respect than others, but even their behaviour is not perfect. A complimentary approach is to measure the vertical speed directly (using a vertical propeller anemometer or a 3D sonic

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[8] 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.

anemometer) and then remove its effects from the cup anemometer data, assuming the anemometer's vertical response characteristics are known.[9]

Icing. The build-up of ice can cause problems for any anemometer. (The same applies to direction vanes.) For cup anemometers, ice can make the shaft rotate more slowly or freeze entirely. Naturally this is not a problem for most tropical islands, but if your project is in an area that might be prone to icing, it is best to replace some of the planned anemometers with a heated anemometer. You should not use heated anemometers exclusively, however, as they are generally less accurate than unheated ones (except when there is icing), and they also draw much more power. In a typical configuration, a heated anemometer is paired with an unheated one on each of the top two levels of the mast.

Power consumption. Most instruments intended for wind resource assessment are designed to consume as little power as possible. However, certain types of anemometers, such as heated anemometers and sonic anemometers, consume much more than others. This is not an issue if you have access to grid power, but if you do not, the power draw needs to be considered both in the sensor choice and in the design of the power supply. (Power supply options are discussed in section 7.6.)

Wind Direction

Second in importance only to wind speed, the wind direction is a necessary ingredient for modelling the spatial distribution of the wind resource across a project area and for optimising the layout of the wind turbines. The direction is usually measured with a wind vane. (With prop-vane and sonic anemometers, no separate vane is required.) In the most familiar type, a tail assembly is connected to a potentiometer and rotates to align with the wind. A voltage is applied across the resistive element of the potentiometer, and a reading is taken from where the potentiometer's wiper arm makes contact.

Vanes have one significant design limitation: they cannot read the direction where the two ends of the resistive element meet, called the deadband. This is usually a minor issue as the deadband is narrow and should be oriented in an infrequent wind direction.

Air Temperature

Measurements of air temperature are used to estimate the air density (see Equation 3-5 and 3-6). They also help flag the occurrence of icing and estimate the frequency of low- or high-temperature shutdowns of wind turbines. 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. 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 affected by direct sunlight.

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[9] 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.

Additional Measurements

Depending on the site conditions and the needs and priorities of the monitoring programme, additional sensors may be included. Table 7-2 lists the nominal specifications for the most

Table 7-2 Specifications for additional sensors. (Source: AWS Truepower)

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

common sensors. Bear in mind that each additional instrument may require power, and that there are limits to the number of instrument channels supported by data loggers.

Vertical Speed

In complex terrain (defined by the IEC as having a slope of more than 10% within a distance of 20 times the hub height from turbines),[10] it is recommended that the vertical wind speed be measured. This can improve the estimate of the horizontal wind. In addition, it can be an important input for turbine loading and suitability calculations, as severe or frequent off-horizontal winds can cause damaging loads and wear.

Since vertical motions are often very small, an anemometer of unusual sensitivity and low starting threshold is called for. Also, the anemometer must be able to distinguish between

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

upward and downward winds. For these reasons, cup anemometers cannot be used. Two common approaches for measuring the vertical wind speed are to mount a propeller anemometer with its axis pointed vertically or to use a sonic 3D anemometer. The 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. 3D sonic sensors are more expensive but offer the advantage of measuring both vertical and horizontal wind components simultaneously.

Barometric Pressure

Barometric pressure can be used with air temperature to determine air density. Since is difficult to measure accurately in windy environments, high-quality barometers are quite expensive. As a result, most resource assessment programmes do not bother with them, and instead rely on temperature and elevation alone. This is adequate under most conditions. The main exceptions to this rule are sites at especially high elevations (greater than 2000 m above sea level). In those cases, it is recommended that high-accuracy air pressure measurements be made.

Several suitable 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. If barometric pressure measurements are required at a site, 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.

Delta Temperature

At some sites it may be useful to measure the temperature change (delta) with height, especially for understanding and modelling the effects of thermal stability on wind shear and wind flow. To do this, exceptionally accurate temperature sensors are required. Such sensors are purchased as a matched pair, which have been calibrated to provide the necessary accuracy. When such sensors are deployed, of course, there is no need for any other air temperature sensor.

Solar Radiation

It is sometimes desirable to measure solar radiation as part of a wind monitoring programme. One purpose may be to assess the same site for solar energy. Solar radiation can also be an indicator of atmospheric stability, knowledge of which may assist in understanding and modelling the wind resource. The most common parameter of interest is the global horizontal (total) solar radiation, which is the combination of direct sunlight and diffuse sky radiation striking a horizontal plane. It is measured with a pyranometer. The data logger (or a supplementary interface device) converts the pyranometer signal to solar radiation. 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. Note they may require frequent maintenance visits for cleaning and re-levelling.

Sensor Calibration

All sensors have a transfer function, which converts the instrument's signal (such as a voltage or frequency) to a physical parameter such as wind speed or air temperature. For anemometers, that function is typically a linear equation with a constant slope and offset:

$$v = sf + c \qquad \text{Equation 7-1}$$

where *v* is the wind velocity, *s* is the slope, *c* the offset (which may be zero), and *f* the frequency (or sometimes voltage) produced by the anemometer. This equation may be defined in the data logger, or can be applied afterwards during the data analysis.

Given the importance of wind speed in determining energy production, having an accurate anemometer transfer function is essential. The default slope and offset are usually defined by the manufacturer (or sometimes by a consensus of the community) on the basis of numerous tests. Sometimes, however, an anemometer is tested (for a small additional cost) in a certified wind tunnel before it is purchased. In that case it said to be *calibrated*.

Using either calibrated or uncalibrated anemometers is generally acceptable. One advantage of using calibrated ones - 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.

Besides anemometers, temperature sensors, barometers, and pyranometers can be calibrated as well. In small or cost-constrained monitoring programmes, however, this is usually unnecessary.

Accuracy and Reliability

Sensor 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 7-1 and Table 7-2.

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 usually 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.

The system error is typically expressed in one of two ways:

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

$$|Measured\ Value\ -\ Accepted\ Standard\ Value|$$

As the absolute percent difference with respect to the accepted standard value (as in, for wind speed, ≤3%), calculated as

$$100 \times \frac{|Measured\ Value\ -\ Accepted\ Standard\ Value|}{Accepted\ Standard\ Value}$$

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.

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, and other users can be contacted at conferences and workshops.

7.3 SENSOR HEIGHTS AND CONFIGURATIONS

The heights and configuration of sensors – especially anemometers – can have a significant impact on the quality of a wind resource measurement campaign. With an insufficient number or poor choice of heights, you might not get an accurate measurement of the wind shear and hub-height wind speed. With improper configuration and orientation of the mounting boom (a horizontal support which positions the anemometers away from the tower structure), tower influences might affect the accuracy of your wind measurements. This section provides guidance on wind industry best practice for determining sensor heights and configurations.

Anemometer and Vane Heights

The following guidelines govern the selection of anemometer and vane heights for most island sites:

- Every tower should have at least two levels of anemometers, and preferably three.
- One of the heights should be as close as possible to the expected turbine hub height.
- The highest anemometers, if mounted on horizontal booms, should be at least the same vertical distance below the top of the tower as the horizontal booms are mounted off the side. This is intended to minimise effects of flow over the top (known as 3D flow effects).
- The lowest anemometers should be mounted above trees, buildings, and other obstacles.
- Within the above limitations, the heights should be spread as widely apart as possible to minimise the uncertainty in wind shear.

- Anemometers should not be placed near obstructions (such as communications antennas), or just below guy wire rings.
- Every tower should have at least two levels of wind vanes, and the vanes should be installed on booms that are 1-2 m below the nearest 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, as discussed below.

Table 7-3 Example monitoring heights for a range of turbine hub heights typical for islands. (Source: AWS Truepower)

Hub Height	Tower Height (m)	Example Anemometer Heights (m)	Example Vane Heights (m)
30	30	15, 27	13, 25
37	34	15, 31	13, 28
55	40	20, 30, 37	28, 35
60	50	25, 35, 47	33, 45
80	60	32, 47, 57	45, 55

While every situation is different, Table 7-3 gives some examples of suitable tower and anemometer heights for different turbine hub heights. As noted in Section 5.1.2, the selected hub heights for island environments are often lower than those for mainland projects. This is illustrated in the table below, which provides example monitoring heights for given turbine hub heights. The direction vanes are suggested to be placed 2 m below the anemometers. (It is assumed that surrounding trees and buildings are less than 15 m in height.)

Other Instrument Heights

There is a good deal more flexibility in where to place most sensors other than anemometers and direction vanes. Typical heights are indicated in Figure 7-7 and Figure 7-8. Keep in mind that the additional sensors should not be placed near a direction vane or anemometer. It is wise to keep a vertical separation of at least 1 m between all instrument heights on a tower.

Within that constraint, vertical anemometers should be placed as near the hub height as possible to obtain the best reading of vertical speeds that might be experienced by a turbine. Delta-temperature sensors should be placed as far apart in height as possible to obtain the most accurate measurement of the temperature gradient; however, the lower sensor should typically be placed at least 10 m above the ground to avoid the influence of near-surface heating. The other sensors can be placed at pretty much any convenient height; those shown are typical.

Instrument Configuration

All sensors, and especially anemometers, should be mounted in a manner that minimises 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 7-7 and Figure 7-8 for tubular and lattice towers, respectively.

Minimum Offset Distance

Most anemometers and direction vanes are mounted on relatively short vertical masts (called *stub masts*) attached to the ends of long horizontal booms. This configuration is designed to position the sensors far enough away from both the tower and mounting hardware to keep their influence on the measurements small (except when the instruments are directly downwind of the tower).

Figure 7-3 illustrates a typical horizontal mounting boom configuration on a tubular tower, with a sufficient horizontal standoff distance from the mast. This example illustrates redundant anemometry, but single anemometer booms should also meet minimum offsets recommendations.

Figure 7-3. A good sensor configuration. The anemometer booms are long compared to the tower width, and the second anemometer is mounted at the recommended angle from the first. The vane is a good distance below. (Source: AWS Truepower)

The recommended minimum offset distance from the tower depends on the type of tower. For a tubular tower, it is 7 tower diameters. For example, for a 20 cm (8 inch) wide tower, the boom should be at least 1.4 m long.

Figure 7-4 illustrates an insufficient standoff distance from a tubular mast. Booms of this length can cause significant tower effects (both acceleration and shadowing), and will not provide an accurate representation of the expected free-stream wind.

Figure 7-4. A poor sensor configuration. The anemometer booms are too short compared to the tower width, and likely would result in a large influence of the tower on the anemometer readings. (Source: AWS Truepower)

Because lattice towers do not block the wind completely, the recommended distance for them is only 3.75 the face widths for most types. But lattice towers are usually much wider than tubular towers. For a typical face width of 45 cm (18 inches), the minimum distance is about 1.7 m. Thus, lattice towers normally require somewhat longer horizontal booms than tubular towers do. Regardless of tower type, it is important to ensure that the booms have adequate strength or support so that they do not oscillate in strong winds.

Tower and instrument vendors will often supply appropriate mounting hardware. When the hardware is custom-made, it is important to ensure that it is able to withstand the same wind and ice loading extremes as the tower, and not be prone to wind-induced vibration. Also, for anemometers, the length of the vertical stub mast should be at least 12 times the width of the boom to provide an accurate reading of the free-stream wind speed. For the boom, square, hollow tube-stock should generally be used to provide sufficient strength with low weight.

Anemometers and vanes are sometimes mounted on vertical booms above the top of the tower. This is done to obtain the most accurate possible readings. A "goal post" configuration with two such anemometers allows for redundancy. The vertical booms must be long – at least as long as horizontal booms. In practice, a value slightly exceeding this – at least 10 times the tower width for tubular towers and 5 times the face width for lattice towers – is recommended. The main drawback of this configuration is that the data cannot be used to accurately measure shear since anemometers at lower heights are subject to different tower effects. For this reason, a vertically mounted top anemometer does not eliminate the need for horizontally mounted anemometers below the top of the tower.

Redundancy

For at least the top height on the tower, and preferably the top two heights, the anemometers should be deployed in pairs on separate booms pointing in different directions. This redundancy reduces data losses caused by sensor failures and tower shadow. As discussed earlier, it is often a good idea to pair sensors of different models at the same height.

However, when it comes to instrument mounting in pairs at the same height, there can be too much of a good thing. The boom configuration shown in the photograph below illustrates such a configuration.

Figure 7-5. This sensor configuration is not recommended, as interference between sensors could produce inaccurate readings. (Source: AWS Truepower)

Boom Orientation

The recommended orientations of the horizontal booms – the compass direction towards which they extend from the tower – largely depend on the wind direction distribution at the site. The main goal is for the anemometers and direction vanes to be downwind of the tower as seldom as possible. (This so-called tower shadow produces a large decrease in wind speed as well as shifts in direction.) In addition, the orientations should minimise secondary tower influences in the most frequent wind directions. This section shows how these goals can be met.

Of course, it is impossible to know the wind direction distribution in detail before the measurement campaign begins. Nevertheless, you can usually define the prevailing, or most common, directions based on an understanding of the local wind climate and the influence of the terrain. Some of the same data sources mentioned in Chapter 5 can be helpful for this purpose. The example wind rose shown in Figure 7-6 is typical of a tropical island exposed to easterly trade winds. The wind in this case comes almost entirely out of the east and east-northeast. Wind roses in other locations can show much more directional variation, however.

If there is a strong primary direction, then it is easy to define the directions of the booms at each height. The recommended configuration on tubular towers is for the booms to be oriented 90° apart from each other and 45° on either side of, and facing into, the prevailing wind direction (Figure 7-7). This is better than putting the booms 180° apart, which would seem to be the natural choice, because in that configuration there is a significant tower-induced acceleration of the wind at the point where the speed is most often measured.

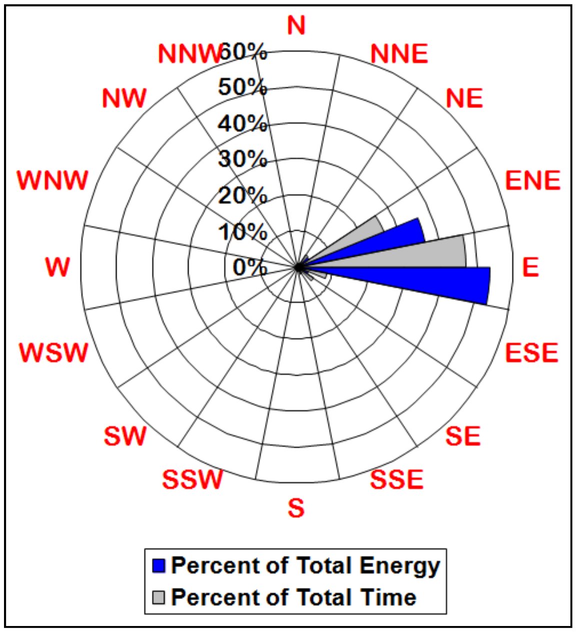


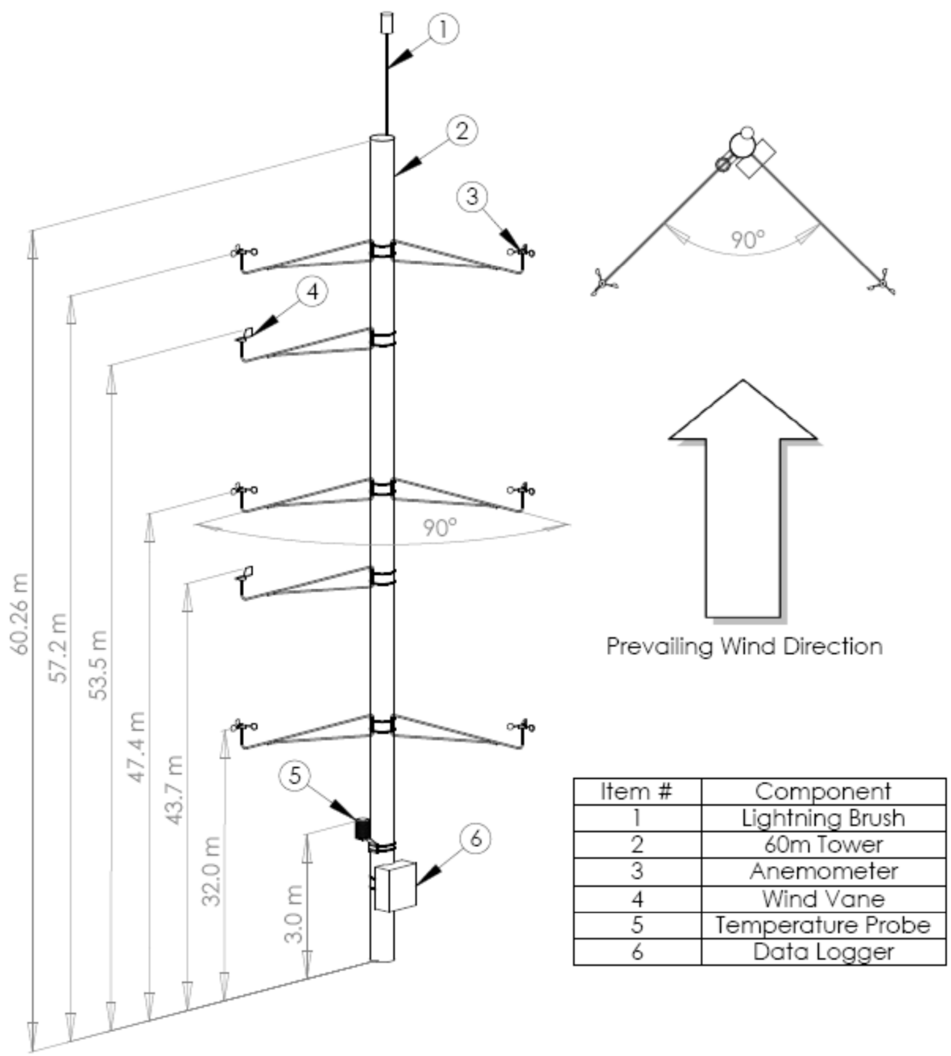
Figure 7-6. Sample wind rose for a trade wind climate.

The options for lattice towers are more limited, since booms are usually attached to, and hence parallel with, the tower faces. On square lattice towers, the recommended configuration is to place the booms 90º apart with the same orientation to the prevailing wind as that recommended for tubular towers. On triangular lattice towers, the booms are best mounted 60º on either side of the prevailing direction (Figure 7-8). Whether these orientations will be possible depends on whether the tower faces were oriented correctly at the time the tower was erected. If not, then you will have to find a reasonable compromise that satisfies the objectives.

It may also be necessary to depart from the guidelines if there are strong secondary wind directions. For example, if the wind comes from the east and west with equal frequency, it would be best to mount the anemometers towards the north and south, 180º apart. The charts in Figure 7-9, which show typical patterns of wind flow disturbance around tubular and triangular lattice towers, can help guide boom placement in such situations.

Anemometers at different heights should be mounted on horizontal booms pointing in the same direction off the tower. This configuration minimises 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.)

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 much time in the deadband, it allows the deadband orientation to be easily verified from the ground with a sighting compass or sub-meter GPS.Also, 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.



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 7-7 This diagram illustrates a typical recommended mounting configuration for a 60 m tubular NRG Tall Tower. (Source: AWS Truepower)

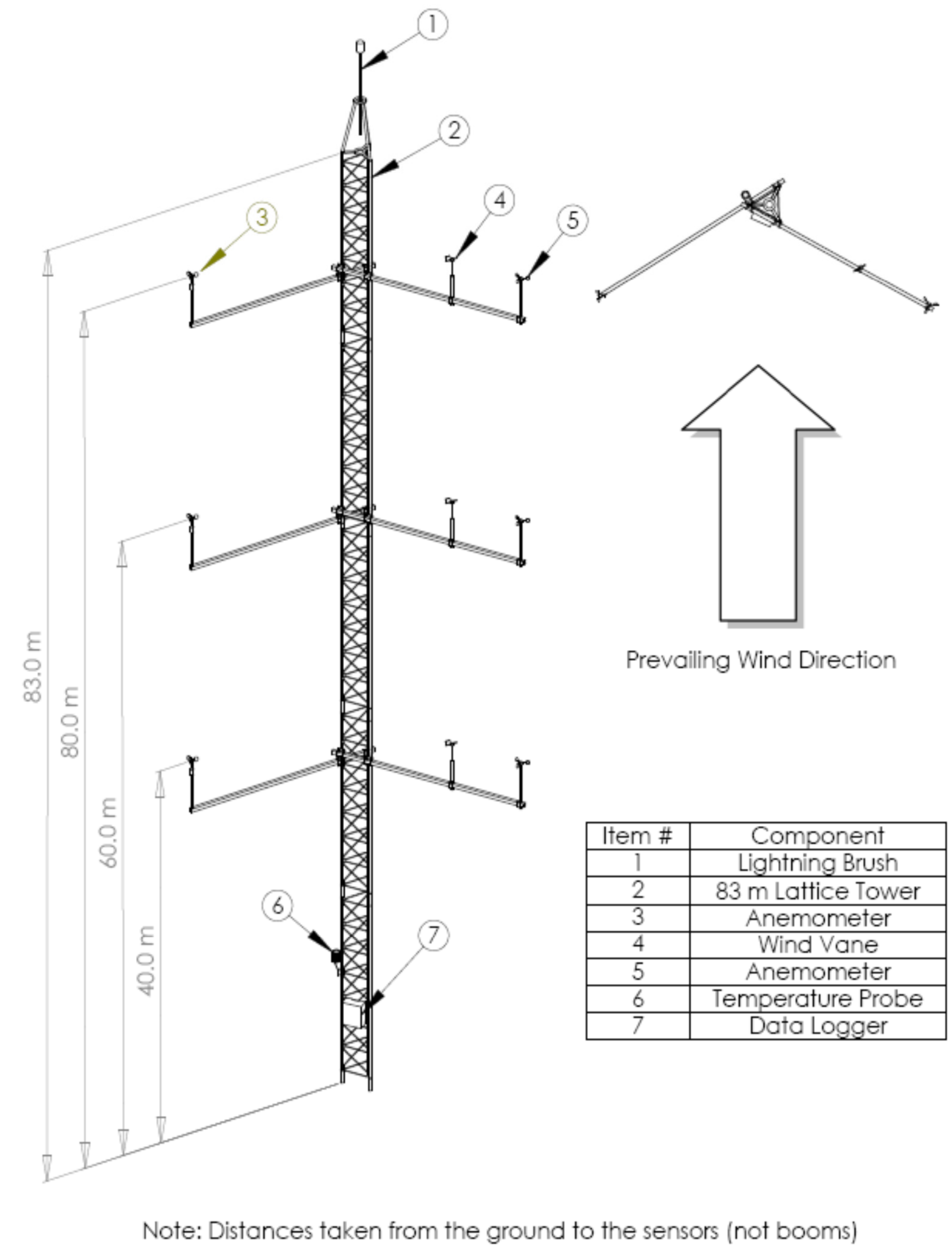


Figure 7-8 This diagram illustrates a typical recommended mounting configuration for a 83 m guyed lattice meteorological tower. (Source: AWS Truepower)

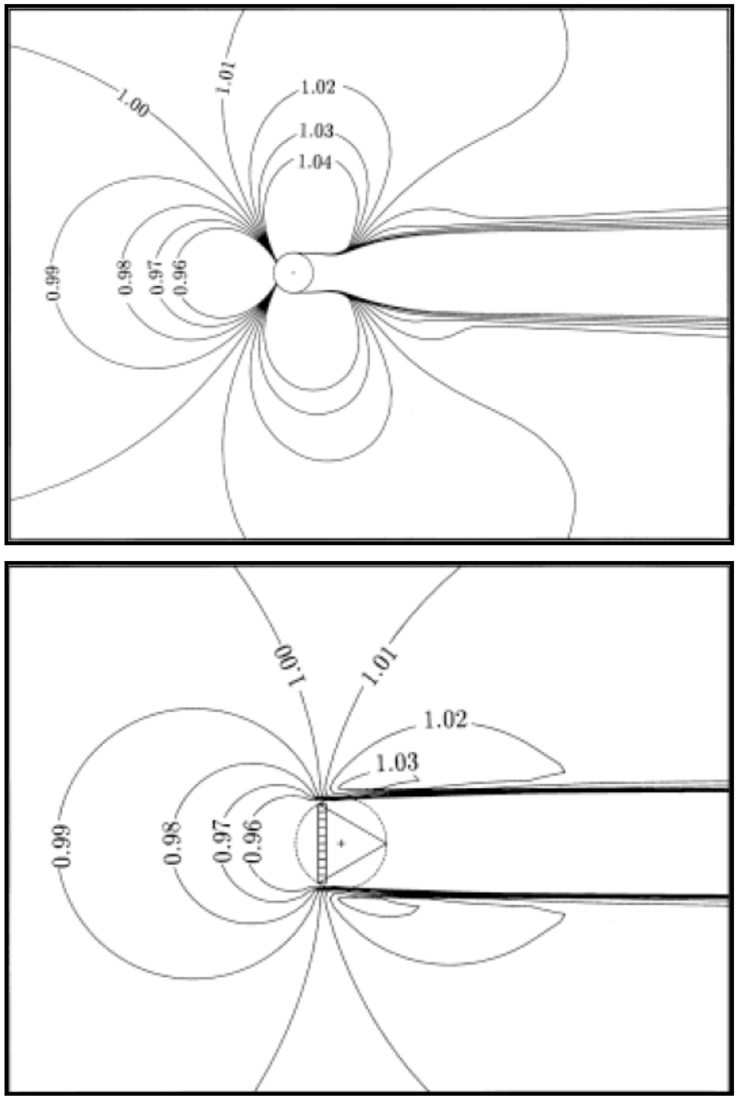


Figure 7-9 The above diagrams illustrate how the airflow is distorted close to a tower. A tubular tower is portrayed on the top, and a lattice tower at the bottom. The wind approaches from the left side of each image. The contours illustrate the impact of the tower on the free-stream speed. For example, the 0.97 contour indicates that the tower reduces the expected free-stream wind speed by 3%. (Source: IEC 61400-12, Annex G – Mounting of Instruments on the Meteorology Mast.)[11]

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Temperature and other supplemental measurements, as well as communications equipment such as antennas, are often mounted near the tower base. In many cases, a pressure sensor can be mounted inside the logger box, while the remaining sensors must be mounted outside. Where security requirements dictate, any equipment near the tower base can be moved up the tower as necessary. Typical monitoring requirements for ancillary sensor types are presented in Table 7-2.

7.4 DATA LOGGERS

Data loggers are devices that record data from sensors for later retrieval. All loggers store data locally, and many can transfer 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.

Specifications

A number of data loggers suitable for wind resource measurement are commercially available. A vendor list is provided in Chapter 9. Many instrument manufacturers offer complete data-logging systems that include integrated storage and transfer options. A suitable logger should have the following characteristics:

- Be able to store data values in a sequential format with corresponding time and date stamps
- Possess an on-board real-time clock with battery backup so that the time stamps will remain accurate even if the logger loses power
- Have an internal data storage capacity of at least 180 days (the longer the better in remote locations)
- Operate in the same environmental extremes as those listed in Table 7-1
- 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.

You should always check with the manufacturer to make sure a logger is compatible with the number and types of sensors you will be mounting on your tower. Data loggers have a limited number of channels, some of which may be designed only for digital sensors (frequency counters) or only analogue sensors (voltage or current). It is important to be sure that there are enough channels of each type for the sensors you plan to deploy.

Data Sampling and Recording Intervals

The data sampling interval is how often the data logger samples the value from each sensor. A typical rate is once every one or two seconds, depending on the logger model. (For sensors that generate digital counts, such as most anemometers, the sampling frequency should not be greater than the pulse frequency to avoid oversampling errors.) It is usually impractical (as well as unnecessary) to store this much data, however, except for special applications. Instead the data logger calculates and stores statistics from the sampled data over a longer recording interval. The industry-standard recording interval is 10 minutes, though occasionally other (usually shorter) intervals may be used.

Statistics

The standard statistics calculated by the data logger are listed in Table 7-4 and described below.

Table 7-4. Statistics stored by data loggers

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

- Average. The average or mean value in each ten-minute interval is recorded for all parameters shown in the table 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.

- Standard Deviation. The standard deviation should be determined for both wind speed and wind direction and is defined as the population standard deviation (σ) of all values within a recording interval.

- Maximum/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.

System Configuration and Customisation

The many loggers available on the market vary widely in their sophistication and customisability. Some units are nearly completely self-contained, requiring minimal programming and featuring preset recording intervals and numbers and types of instrument inputs. Others are fully customisable with advanced programming and recording capabilities and the ability to record data from tens of sensors. In some loggers, the signals can be interpreted with user-specified commands or programming, while in others specialised hardware interfaces are required for different instrument types. In recent years, the trend in the data logger market has been toward increasing the number of available instrument channels; however, there is generally less flexibility in the recording interval.

Data Storage Options

Every modern 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 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 11). 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. However, 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 storage media are typically able to store at least 6-12 months of data, unless the recording interval is much less than the usual 10 minutes. A minimum of 6 months' uninterrupted storage capacity is recommended, especially in remote locations.

Most manufacturers offer several options for data storage devices. The most common are presented in Table 7-5 and examples are shown in Figure 7-10. Most of these options are relatively inexpensive and readily available. Best practices for data handling and storage are discussed in Chapter 11

Figure 7-10 – Example storage devices

Table 7-5 Data storage devices.

Storage Device	Description	Download Method/ Needs
Memory card	Independent memory chips in numerous formats (*e.g.* MMC, SD, micro-SD, 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.

7.5 DATA TRANSFER AND COMMUNICATIONS

The data stored in loggers must eventually be retrieved. The design of the data transfer and communications systems and protocols depend on the measurement programme's resources and requirements. Typical items to consider include how frequently the data are to be reviewed (whether weekly or monthly status checks and reports are to be performed), the time and effort needed to get to the site for manual retrieval, and the availability and cost of remote data transfer methods. Other factors include the file sizes to be retrieved and the capacity of the logger's memory. This section illustrates some typical data transfer and site communications considerations and options.

Manual and Remote Data Transfer

Data can be retrieved from a logger either manually or remotely. Remote retrieval is usually the more convenient and less expensive option, but it may not be practical in island settings where cellular coverage is poor. You should decide which method you will use before ordering the equipment. Several factors must be weighed in this decision, including labour costs, site access, and cellular or other remote communications availability. Many of these factors can be investigated during the site selection phase.

Manual retrieval requires visiting the site. During a typical visit, the existing storage device (*e.g.* a data card) is removed and replaced with a fresh device, and is then taken to another location where the data are downloaded to a computer. Alternatively, the data can be transferred directly to a laptop at the site, and the storage device is left in place.

Manual retrieval is perfectly acceptable, but it has disadvantages including additional data handling steps, which increase the risk of data loss, and the need for frequent site visits (at least once every two weeks, and preferably more often) to minimise the amount of data that might be lost if a sensor or the logger malfunctions between visits. Most often, the main reason to choose manual data retrieval is if there is no reliable way to obtain the data remotely.

Remote transfer requires a telecommunications link between the data logger and the central computer. Most common are cellular and satellite data links. Other options include direct-wire cabling and radio frequency (RF), but these are rarely used.

The main advantage of remote methods is that the data can be retrieved and inspected more frequently (*e.g.* daily or weekly) than may be practical with site visits. This means that problems with the sensors or logger can be more quickly identified and resolved, thus reducing data losses and improving data recovery. The cost of the equipment and data service need to be weighed against the cost of labour to visit the site for manual retrieval. In addition, some sites have poor cellular coverage, and other telecommunications options can be expensive.

Data loggers equipped with cellular data links are popular and widely available for a reasonable price. The cellular signal strength and type (GSM or CDMA) at the site should be determined in advance; this can be done with a portable telephone. Where the signal strength is weak, an antenna with higher gain can sometimes work. Failing that, a satellite modem linking into the Globalstar or Iridium global network is an option, though a comparatively expensive one.

Data Transfer

For most resource measurement campaigns, the amounts of data to be stored and transferred are well within the capabilities of modern data loggers and computers. The exception to this rule is when the data recording interval is much shorter than the usual 10 minutes. High-frequency data collection is sometimes desirable to assess the variability of winds for integration on power systems. In this case, more frequent site visits or data retrievals may be necessary, or onsite data storage may have to be supplemented with additional storage or other options such as laptop computers or hard drives.

Where wireless or satellite data transfer networks are available, transfer speeds are not normally a concern since the data files generated by loggers at the standard recording interval are quite small. Loggers can be configured to connect repeatedly until a successful transfer is made. With high-frequency data collection, however, or when multiple towers are being transferred over the same connection, network reliability and speed can become limitations. The cost of transferring large amounts of data should also be considered, as many telecommunications companies charge by data volume. A good compromise in such a situation is to store high-frequency data on site, to be retrieved manually from time to time, while the much smaller 10-minute data files can be retrieved remotely on a daily or weekly basis.

7.6 POWER SUPPLY

All wind measurement systems require a power source. The leading power supply options for instrumented towers 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. This may be adequate for a tall tower equipped with the standard sensors. However, although the systems are generally reliable, data will nonetheless be lost if the batteries fail. In addition, household batteries are not sufficient for towers with heated sensors, sonic anemometers, or other special power needs. To address these issues, the logger 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 which encapsulate the acid in a gel or paste to prevent spills, called non-spillable or gel batteries, be used.

The solar panel should 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. Further, it must include a voltage regulator to supply a voltage compatible with the battery and to prevent overcharging during months with the most sunlight. Most logger vendors offering solar-battery packages will advise on the proper size for your 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 tower 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.

Other Power Options

Other power sources that may be used in some circumstances include small wind systems, wind/solar hybrid systems, diesel or gasoline generators, and fuel cells. Small wind and wind/solar hybrid systems can be a good choice where there is plenty of wind and solar radiation is limited (in arctic environments, for example), or where solar panels are likely to be blocked by trees or other obstacles much of the time. Figure 7-10 illustrates two skid-mounted solar/wind/battery autonomous power supplies, designed for operating lidars in cold environments. Diesel or gasoline generators are sometimes used for remote sensing systems, but are usually overkill for tall towers without heated sensors. Fuel cells powered by methanol, propane, or other fuels are available for applications where large, continuous power is required. They are usually more expensive than generators, but are quieter. They can be used to power autonomous remote-sensing systems where increased power draws due to system heating or cooling are expected. Partnerships with local or regional universities or companies may yield some interesting opportunities.

Lighting

In some regions, towers taller than a certain height may need warning lights. This should be checked with the appropriate regulating agencies. The position of the lights should be considered in the monitoring design to minimise interference with anemometers and other sensors. Also, the need to power the lights should be considered in the choice of power supply. Where there is no grid power, warning lights can be operated by a photovoltaic-battery system.

7.7 POINTS TO REMEMBER

- The two main types of instrumented tall towers are tubular tilt-up and fixed lattice. Both have advantages and disadvantages, depending on the specific site. Another option is to use an existing communications tower.
- Instrument mounting configuration is a critical component regardless of the tower type used. The equipment should be durable and mounted in a way that prevents movement and allows for consistent operation and safe maintenance.
- Anemometer selection is often dependent on programme objectives and budget, with many options available. Redundant instrumentation is suggested, while proper orientation and standoff distances are important to minimise tower effects.
- Other meteorological parameters (especially wind direction and temperature) are essential in characterising the wind resource of a site; other useful atmospheric parameters be can beneficial and easily measured at low cost.
- A variety of data logging and storage options exist. The paramount concern in selecting this equipment should be reliability, data recovery, and data protection. Remote data transfer is usually the most cost-effective option, but may not be feasible at sites with no cellular coverage. In that case, manual retrieval will be necessary.
- Solar-battery systems and household batteries are the most common power sources for tall towers. Most tall tower monitoring campaigns do not require grid power, unless it is necessary to power aviation or obstruction lights.

Figure 7-11- Two skid-mounted autonomous power units employing solar and wind systems and battery storage.

8 REMOTE SENSING SYSTEMS

In the past several years, ground-based remote sensing has become a realistic option for many wind resource measurement campaigns. It offers particular advantages at large, complex sites, where its mobility can allow the resource to be spot-checked at multiple points; for projects where very large turbines are likely to be used; and where there is substantial uncertainty in the wind shear. It can also be useful at sites where it is impractical or too expensive to install a tall tower.

This chapter introduces the two main types of remote-sensing technology, sodar and lidar, and describes current industry-accepted practices for integrating them into wind resource measurements programmes.

8.1 SODAR

Sodar (sonic detection and ranging) operates by emitting acoustic pulses (audible chirps or beeps) upward into the atmosphere and receiving 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 analysed 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 the sodar principle, and Figure 8-2 shows two commercial sodar models.

A typical sodar system is equipped with a series of speakers, which function as both 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 weather. 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, discussed below) 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 (see section 8.4). 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 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 scrutinised and likely removed from the sodar data stream.

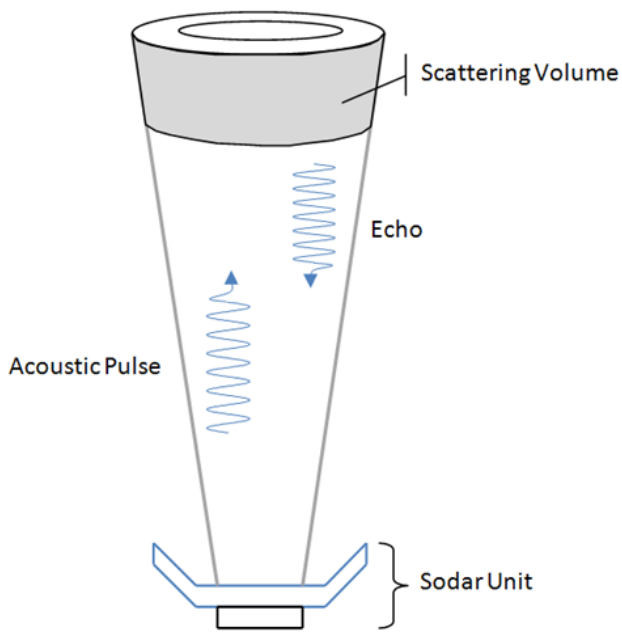

Figure 8-1 Illustration of sodar operation. The sodar unit emits an acoustic pulse and subsequently measures the backscatter from the scattering volume to determine the wind speed.
(Source: AWS Truepower)

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

8.2 LIDAR

Lidar (light detection and ranging) most commonly operates by emitting a laser light signal (either as pulses or as a continuous wave) which is partially scattered back in the direction of the emitter by aerosol particles carried by the wind. The light scattered from these moving 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 three 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 over 10 kilometres. While the scanning lidars have the potential for significant advancement in wind resource assessment, this document focuses on the more widely used 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 may have on-board battery back-up in case of a grid outage, a separate power supply must usually 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 Two commercial lidar units: a Leosphere Windcube V1 (left) and a 150-series ZephIR. (Source: AWS Truepower)

Lidars designed for wind energy applications came on the scene after sodars and are more expensive. Nevertheless, their popularity is growing. Lidars have benefited from testing campaigns that have helped to establish a reputation for accuracy. In addition, they are increasingly being considered for specialised applications, such as power curve measurement, offshore wind resource assessment, replacements for nacelle anemometers, and deployment within and around existing wind farms for performance measurements and real-time forecasting. The use of lidar is expected to continue growing in the future as prices decrease and experience with and acceptance of the technology increase.

8.3 MEASUREMENT PARAMETERS AND DATA RECORDING

Both sodar and lidar systems output multiple parameters. Primary outputs for each monitoring level include horizontal wind speed and direction, vertical wind speed, 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 essential 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 towers and remote sensing systems at a project site should be synchronised.

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 5 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.

8.4 COMPARISONS WITH CONVENTIONAL ANEMOMETERS

With ground-based remote sensing only recently becoming widely used for wind resource measurements, much attention has been paid to comparing their measurements with the industry standard: cup anemometers mounted on tall towers. In many remote-sensing campaigns, the sodar or lidar system is placed for a period near a tower in order to verify the accuracy of their readings and of the data-analysis methods. Once benchmarked in this way, the unit can be moved to sample the resource at other locations, or remain in place to supplement the measurements at the mast.

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 or lidar and cup anemometer measurements be understood and eliminated, if possible. (In some cases, it may be the anemometer readings that require correction for such effects as overspeeding and response to off-horizontal winds or low temperatures.) Without attention to such corrections, deviations of over 5% can be seen between anemometers and sodars or lidars in some environments.

The main factors responsible for biases between sodar, lidar, and ordinary anemometers are discussed below, along with the technology to which they apply (sodar, lidar, or anemometers). With careful siting, campaign management, and data analysis to treat these issues, ground-based remote sensing measurements should be as accurate as 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 typically result in biases of 2% to 3% between a sodar and a nearby anemometer.

Vector to Scalar Wind Speed Conversion (Sodar and 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 output from cup anemometers) for the same time interval. 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 typical vector-to-scalar bias correction is 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 (Sodar, Lidar, and Anemometers)

For most lidars, data recovery depends on the background aerosol level. In especially clean air (*e.g.* high mountain air, and 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.

Data collected from sodars or lidars during periods of precipitation should be scrutinised carefully, and excluded from certain analyses. While the effects of rain and snow on horizontal wind speed measurements may be very small, vertical wind measurements are almost always overwhelmed by the precipitation's downward motion, and should be ignored during these periods.

In cold climates, ice accumulation on unheated anemometers can equally cause discrepancies with sodar or lidar systems. The appropriate use of heated sensors should eliminate this problem.

Turbulence Intensity and Anemometer Overspeeding (Sodar and Lidar)

As noted earlier, cup anemometers tend to overestimate the mean wind speed in a turbulent wind because they speed up in a gust more quickly than they slow down after the gust passes. This effect varies significantly by sensor model. Under such conditions, it can appear as if the sodar or lidar is underestimating the speed, when it is actually the anemometer that is overestimating it. Since the dynamic responses of most anemometers are known, methods are available to adjust the anemometer data for overspeeding. This topic is addressed in Chapter 12. The turbulence adjustment is typically on the order of 1-3% of the observed speed, but depends on site conditions and instrument model.

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. The calculation assumes flow homogeneity over that volume. In simple terrain and moderate shear conditions, this assumption typically results in very comparable readings between remote sensing systems and anemometers. However, in some cases, volume averaging can lead to deviations between sodar, lidar, and anemometer measurements.

Each layer measured by sodar (regardless of the height interval at which speeds are reported) represents an integral of information across a depth of 20 m or more. In layers where there is high wind shear, this averaging can cause the sodar to underestimate the mean speed at the nominal measurement height by up to 3%. Very low or negative shear can have the opposite effect.

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 shallow depths, the potential bias is minimal. With depths of 20 m or more, extreme shears can introduce biases similar to those seen in sodar systems.

Flow Inclination (Sodar, Lidar and Anemometers)

At sites where significant vertical winds occur (due to steep terrain, for example), a correction to anemometer readings may be required to bring them into alignment with sodar or lidar. Cup anemometers vary considerably in their response to vertical winds, and expert help may be needed to determine the appropriate correction. In most cases, the adjustment is less than 1%, but in extreme slopes adjustments of up to 3% or more may be necessary.

Variations in the flow inclination across a lidar or sodar system's measurement volume, which often occur in complex terrain, can cause biases of 3-5% in their measurements, as well. The effect will vary with the system's characteristics, terrain complexity, land cover, and weather conditions. This topic is an area of ongoing research and investigation. Reconciling anemometer and remotely sensed measurements at highly complex sites may require bringing additional tools to bear including high-resolution wind flow modelling and high-frequency, three-dimensional point and volume measurements.

Distance from Reference Mast (Sodar and Lidar)

Some types of sodars and lidars must be placed a considerable distance from a reference mast to minimise the mast's interference with the measurements. Even where this is not the case, it is sometimes desirable to place the remote sensing unit away from a tower. In moderate and complex terrain, and where there are significant variations in land cover, this can create apparent discrepancies between measurements which are due to real differences in the wind resource. Assessing the significance of these discrepancies requires expert judgment, possibly aided by numerical wind flow modelling.

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 nearby, high-quality anemometer at the same height.

8.5 INDUSTRY ACCEPTANCE AND "BANKABILITY"

Until now, ground-based remote sensing has been used mainly to complement wind resource measurements by tall towers rather than as the sole source of data. In the most widely accepted practice, the vertical profiles measured by a sodar or lidar are used merely to verify or adjust the extrapolated profile from a nearby tower. Less frequently, a system is used directly to measure the resource at different points in a project area, though still in conjunction with one or more towers. In only a few situations – such as offshore, or other locations where tall towers are impractical very expensive to install – are sodar and lidar systems likely to be used alone.

The degree of acceptance of sodar and lidar technology is rapidly evolving, however. As the commercial availability and use of remote sensing units (particularly lidar) for wind resource measurement have grown in recent years, different stakeholders have been gaining exposure to and experience with these systems. Numerous academic, government, and private groups, as well as manufacturers, have published guidelines and research results, including assessments of the accuracy of different lidar and sodar models compared to cup anemometers. As a result, confidence in the technologies is growing.

The attitudes of financial institutions regarding the "bankability" of standalone remote sensing are often key to determining how the technology may be used in a resource measurement campaign. Where external financing is likely to be needed, upfront discussions with lending institutions and experienced consultants are a must. On the other hand, for projects that are being financed by other means – such as through utility revenues or community funds – it may be easier to rely on remote sensing, so long as rigorous standards are applied to the measurement campaign and data analysis. In either case, validation of sodar and lidar data against concurrent tall tower measurements will be helpful for winning the confidence of stakeholders.

In summary, while the "bankability" of remote sensing is not at the level of conventional measurements, strides continue to be made. Project-specific considerations include whether the project requires external financing, the variation in wind resource across a proposed project area, the likelihood of significant changes in wind shear with height, the availability of comparisons of particular lidar or sodar systems against known benchmarks, and the presence of other on-site measurements.

8.6 POINTS TO REMEMBER

- Sodar and lidar technology most commonly operate by analysing a frequency (sound and light, respectively) shift scattered back to the source from the atmosphere
- A key advantage of remote sensing devices is their ability to measure wind speeds up to and through the rotor plane of many modern wind turbines, in many cases up to 200 m or above. Measurement heights can often be configured in the software.
- Remote-sensing systems tend to be more expensive than tall towers, and require additional expertise and training for maintenance and data analysis.
- Remote sensing systems typically require a smaller measurement area, less site preparation, fewer installation / service staff, less permitting, and shorter lead times for installation and decommissioning compared with typical monitoring towers.
- Remote sensing devices can be operated either in conjunction with a meteorological mast or in a stand-alone capacity. Site-specific options should be evaluated with the programme manager, lending institutions, experienced consultants, and any other interested parties.
- Differences exist in the measurement of the wind resource between conventional anemometry and remote sensing systems. These differences must be accounted for in the data evaluation process.
- Remote sensing systems are gaining acceptance within the industry and financial community. Before it is decided to use a remote-sensing system, however, the relevant parties should be approached to discuss the potential benefits and disadvantages.

9 INSTALLATION OF MEASUREMENT SYSTEMS

The installation phase of the monitoring programme can proceed once the site selection and wind monitoring system design have been completed, all required permits have been obtained, and the necessary land leases or other agreements have been executed. This chapter provides guidelines on key installation steps, including equipment procurement, inspection and preparation, installation, site commissioning, and documentation.

9.1 EQUIPMENT PROCUREMENT

The first step in the process is to procure all the equipment – including towers, communication and data storage equipment, sensors, loggers, mounting hardware, cabling, and others – that will be required based on the design specifications of the measurement programme. The design may specify the brand and model of sensor or other hardware to be used, or that may be left to the discretion of the programme manager. Another decision to be made is the number of spares (if any), as well as ancillary hardware and software ranging from laptops and office software to lightning rods and memory cards.

It is always a good idea to obtain price quotes from competing suppliers and manufacturers. Factors to consider in comparing quotes include warranties, product support, and delivery options and dates. 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. Ordering complete packages of equipment – such as sensors, data loggers, storage, telecommunications, and power supply – from a single vendor can save time and money, and ensures the equipment will be compatible.

How and where the equipment is to be delivered is also an important consideration in choosing a supplier, especially on islands with limited transportation facilities. The delivery location should be one where the necessary tools to safely handle the shipment, as well as an area suitable for weatherproof, safe, and secure equipment storage, are available. (The storage area may also be used to perform acceptance testing and field preparation.) In some cases, a supplier may not be able to organise the delivery all the way to the desired location, and may instead deliver it to the dock. If so, you will need to make other arrangements to get the equipment where you want it.

Ensuring that the shipment is handled with proper care is essential, and may be a particular challenge for islands. For example, most suppliers ship equipment on shipping crates that are designed to be handled with modern forklifts, which may not be available at some island destinations. Compared to a typical mainland delivery, island deliveries may require additional handling steps, resulting in a greater risk of broken or missing parts. Obtaining replacement parts can take weeks or even months, meaning serious delays in the start of the wind resource assessment campaign.

The following sections list some common brands and models of the main types of wind resource measurement equipment. It is not meant to be comprehensive.

Towers

Some companies design and manufacture towers specifically for wind resource assessment campaigns while others are leaders in the communication and radio tower industry and have developed an offering to address the needs of the wind industry. The following list names a few companies but is not intended to be exhaustive. In many locations, a local communication tower specialist may be able to provide the necessary equipment for the wind resource assessment campaign design and specifications.

- Australian Radio Towers (ART) Guyed Lattice and Tubular Tilt-up Towers www.australianradiotowers.com/)
- Renewable NRG Systems Tilt Up Tubular Towers (www.renewablenrgsystems.com)
- Rohn Guyed Lattice Towers (www.rohnnet.com)
- SME Consult Tilt-Up Climbable Lattice Towers (www.smewind.com)
- Sabre Industries – lattice towers and monopoles (www.sabretowersandpoles.com/)
- FLI Structures (www.fli.co.uk/)
- Double-K Consulting, tilt-up lattice towers (www.double-k.eu)

Data Loggers

- Ammonit – METEO-40L, -40M, and -40S (http://ammoint.com)
- Campbell Scientific – Several Systems (www.campbellsci.com)
- Renewable NRG Systems – Symphonie systems (www.renewablenrgsystems.com)
- SecondWind – Nomad2 (www.secondwind.com)
- Thies – DL16, DLx-MET, DLN (www.thiesclima.com)

Anemometers, Vanes, Other Instruments

Cup Anemometers

It is generally recommended that at least one or two anemometers on each tower conform to the IEC Class 1 standard, as these are the instruments used for turbine power curve measurements. The following are examples of Class 1 sensors:

- Met One – 011 E Class One Wind Sensor (www.metone.com)
- Renewable NRG Systems – Class 1 (www.renewablenrgsystems.com)
- Thies - First Class Advanced (www.thiesclima.com)
- Vaisala – WAA 252 (www.vaisala.com)
- Vector - A100LK (www.windspeed.co.uk)
- Windsensor - P2546A (http://windsensor.com/)

Other anemometers acceptable for use in a redundant or secondary capacity include:

- Climatronics - F460 Wind Speed Sensor (www.climatronics.com)

- Met One - 010C (www.metone.com)
- Renewable NRG Systems - #40 (www.renewablenrgsystems.com)
- RM Young – 05103 propeller-vane sensor (www.rmyoung.com)
- SecondWind – C3 (www.secondwind.com)
- Vaisala - WA15 (www.vaisala.com)

Vertical Anemometers

- Climatronics - M102236 Vertical Propeller Anemometer
- RM Young - 27106 Vertical Propeller Anemometer

Sonic Anemometers

- Applied Technologies – full line of ultrasonic anemometers (www.apptech.com/)
- Campbell Scientific - CSAT3 (www.campbellsci.com)
- Climatronics - Sonic Wind Sensor (www.climatronics.com)
- Gill Instrument - WindSonic 2-D Ultrasonic Anemometer (http://gillinstruments.com)
- Lufft – V200 UMB (www.lufft.com)
- Met One - Model 50.5 Solid State Wind Sensor (www.metone.com)
- Thies – 2D and 3D Ultrasonic anemometers (www.thiesclima.com)
- Vaisala – WINDCAP ® WMT700 and WMT52 (www.vaisala.com)

Wind Vanes

- Climatronics - F460 Wind Direction Sensor (www.climatronics.com)
- Met One - 020C
- Renewable NRG Systems - 200p
- Thies - First Class
- Vaisala - WA15
- Vector - W200P

Temperature sensors

- Campbell Scientific
- Renewable NRG Systems
- RM Young
- Vaisala

Sodars and lidars

Sodars

- Atmospheric Research and Technology (ART) - Model VT-1 SODAR System (www.sodar.com)
- Atmospheric Systems Corporation (ASC) - Models 4000, 3000, 2000 (www.minisodar.com/)
- Remtech – PAXS, PA0, PA5 (www.remtechinc.com)
- SecondWind - TRITON Sonic Wind Profiler (www.secondwind.com)
- Scintec Corporation - Flat Array Sodars (www.scintec.com)

Lidars

- AXYS Technologies / Optical Air Data Systems (OADS) (http://axystechnologies.com, www.oads.com/)
  - WindSentinel™ Land Station / Vindicator ® III Laser Wind Sensor
- Lockheed Martin (www.lockheedmartin.com/us/products/windtracer.html)
  - WindTracer®
- Renewable NRG Systems/Leosphere (www.renewablenrgsystems.com, www.leosphere.com)
  - WINDCUBE® V2
  - WINDCUBE®100S/200S/400S
- Sgurr Energy / Halo Photonics (www.sgurrenergy.com, http://halo-photonics.com/)
  - Galion Wind Lidars
  - Stream Line lidars
- Pentalum Technologies (http://pentalum.com)
  - SpiDAR® wind lidar
- ZephIR Laser Anemometer - ZephIR 300 (www.zephirlidar.com/)

9.2 ACCEPTANCE TESTING AND PREPARATION FOR DEPLOYMENT

The following tasks should be performed once the equipment has been received and prior to field deployment.

Acceptance Testing

Given the significant risk of damage in shipment and delivery, it is essential to apply rigorous acceptance tests to the equipment you have purchased. You should check immediately on delivery 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 to the manufacturer for replacement.

The following acceptance testing procedures are recommended.

Equipment Inventory

- Print out the order with a list of equipment, and perform an inventory review to ensure that every piece of ordered equipment has arrived.

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 behaviour 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 stabilised, compare the sensor temperature readings to a known calibrated thermometer if available. Deviations between sensors should not exceed 1°C. A pair of delta temperature sensors should not differ from one another by more than 0.1°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.

Remote Sensing Device – Sodar or Lidar

- Whether the remote sensing system is a sodar or a lidar, the acceptance testing should include the full operation of the device at the delivery location for a period of several days. You might adopt a staged approach where the system is initially powered by the grid, and then if that test is successful, by the remote power supply with the grid disconnected. You should examine the data stream to make sure it is producing reasonable results (wind speeds in normal bounds, good data recovery up to the maximum height specified), without the occurrence of dropped data, system reboots, frozen scans, and other problems that can sometimes occur with such systems.

Field Preparation Procedures

Thorough preparation before going into the field to install equipment can save time and reduces the risk of problems requiring a costly return visit. The preparation should include the following tasks:

- Assign 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 (an example is provided at the end of this chapter).
- Install the data logger's data management software on a personal computer and enter the required information.
- If desired, programme 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 time in the field, assemble as many components in-house as possible. For example, sensors can be pre-wired and pre-mounted on their booms.
- Some sensors are fragile, so properly package all equipment for safe transport to the field.
- Pack all tools and consumables (*e.g.* electrical tape, zip ties, orange flags for safety markers, silicon caulk for corrosion protection) 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.
- Prepare all the necessary hardware for the grounding system (wires, rods, and clamps), as well as the hardware and tools required for the fencing if applicable.

- Contact the landowners to inform them of the upcoming installation and ensure the site will be accessible.
- Ensure that an underground utility survey has been performed and has cleared the process so that anchors and grounding rods can be driven into the ground without any risk.

9.3 INSTALLATION TEAM

The quality of the data collected in a wind monitoring programme depends on the quality of the installation. The installation team must have at least some experienced personnel, one of whom is assigned a supervisory role. An experienced and properly managed team will promote efficiency and safety, and may also win the confidence of financial institutions and their consultants. 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. Labour requirements for installing lattice towers vary, and need to be determined by a qualified engineer or experienced installer. A single technician could perform the deployment of a remote sensing device, but for safety reasons, a crew of at least two is recommended.

The installation team leader should be given instructions on how to reach the site, as well as the landowner's name and contact information to arrange access and coordinate the visit. Also, he or she should 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 measurement location. If the personnel responsible for the site's selection are not involved in the installation, it would be wise for the installation team leader to visit the site in advance to verify conditions and access.

9.4 SAFETY AND SECURITY

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. Radio frequency hazards may also be present, particularly when existing tall towers are used. 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 official or industry-standard safety procedures, such as those governing electrical work, construction work, tower climbing, and others.
- Remain in communication with each other and with the home office.
- Follow all safety guidelines provided by the tower and equipment manufacturer, including wind speed limits for tower installation.
- Use common sense during the installation process. For example, if there is lightning activity, postpone work until the danger has passed.

Figure 9-1 Unsafe climbing practices like those shown here are a serious danger to personnel. In this case, the climber has no head protection, climbing harness, or fall protection. (Source: AWS Truepower)

- 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 organisation 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.

Figure 9-2 Safe climbing practices are shown here. The technicians are working as a team while employing appropriate personal protective equipment, equipment management, and fall protection. (Source: AWS Truepower)

- Install any security equipment that has been deemed necessary for the site. It may include but is not limited to: fences around the tower base and anchors to preclude cattle from leaning on the equipment or chewing on sensor wires, anti-climbing equipment on the tower and high fences with a lock around the tower base to preclude anyone from damaging the equipment.

Local regulations regarding tower painting and warning lights must be followed. The power requirements for any warning lights should have been considered in the selection of the power supply.

9.5 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 programmes, direction vanes and anemometers are not oriented in the correct, or documented, direction. This can cause significant errors in wind flow and wake modelling 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 the 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 analysed. A better option is to equip the installation team with a Global Positioning System (GPS) receiver configured to indicate true north.

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 9-2. 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 towards true north therefore equals the declination. To the west, the true north bearing is 360° minus the declination. For example, if the local magnetic declination is 10°W, the bearing for true north is °10. If the declination is 10°E, the bearing is 350° (360° - 10°). For a met tower configuration, the same correction method is used to determine information such as boom orientations. For example, if a boom has an orientation of 150° from magnetic north, and the local magnetic declination is 15°W, then the bearing for true north is 15° and the corrected boom orientation is 165°.

9.6 TOWER INSTALLATION

Installing Tilt-Up Towers

Tilt-up towers – both tubular and lattice types – require a clearing to lay the tower down flat as well as provide space for guy wires and anchors. The size of the clearing can be quite large, and is an important consideration in choosing the location, as we saw in Chapter 4. For example, a typical 60 m tilt-up tower is guyed in four directions from the tower. The outermost guy anchor at each corner is about 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 metres (33 ft.) – plus the length of any lightning mast or vertical sensor boom on the top – 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 9-4.) This entire area must be clear, and preferably quite flat, to permit installation.

For tilt-up towers, it is recommended that the guy anchors be located at four of the eight

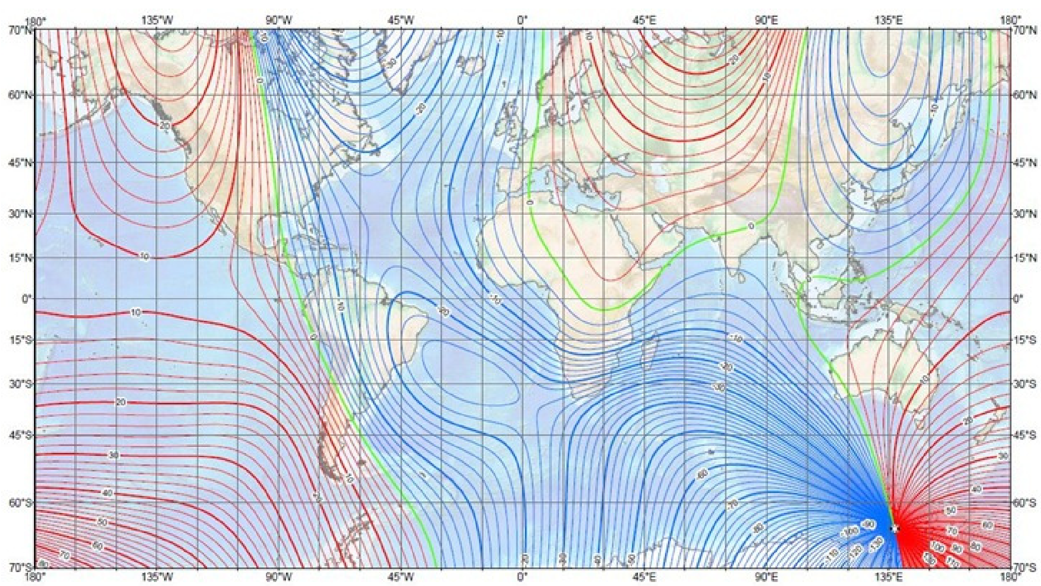

Figure 9-3 Map illustrating magnetic declination for the world in 2004.
(Source: US National Oceanic and Atmospheric Administration)

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 configuration are, first, that it is easy to verify the orientations of the sensor booms by taking a bearing from the prone mast, and second, that 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 main installation steps for a tilt-up tubular tower are listed at the end of this chapter, along with equipment requirements. Figure 9-5 shows a tower being raised into place.

Installing Fixed, Guyed Lattice Towers

Both guyed and self-supporting lattice towers 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.

The main installation steps for a guyed lattice or self-supportive lattice tower are listed at the end of this chapter, along with the equipment requirements.

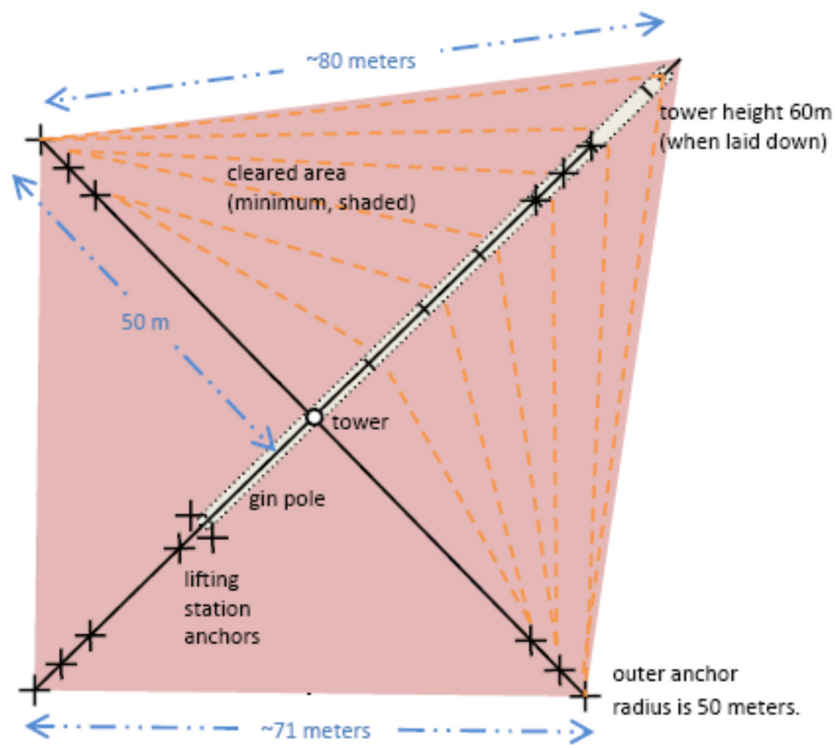

Figure 9-4 The diagram illustrates the footprint of a 50 m tilt-up tower. In this example, the prevailing wind direction is assumed to be from the southwest, and the tower is raised into the wind. The + marks indicate anchor points. The orange dashes represent the guy wires as the tower is being raised, and the black lines indicate the

Figure 9-5 Tilt-up meteorological tower being raised with a gin pole. (Source: AWS Truepower)

Anchors and Guy Wires

The guy-wire system is critical to the structural stability of a guyed tower. Under proper tension, the guy wires keep the tower vertical and minimise sway. Inadequate or uneven tension can cause towers to bend or fall. The anchors must also be able to resist high-wind loads to keep the tower from collapsing. Close attention must therefore be paid to the proper configuration and installation of the guy-wire system.

Anchors come in different types with descriptive names such as screw-in, arrowhead, rock, and concrete. The optimal type for your site depends on the subsurface characteristics, which should have been determined during the initial site investigation. A mismatch between the anchor type and soil conditions could cause an anchor to fail and the tower to collapse. Note that the load-carrying capacity of the soil can vary with time. 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 installation of each guy anchor (and lifting/lowering station anchor for tilt-up towers) should adhere to the manufacturer's instructions. (An example anchor installation is shown in Figure 9-6.) The lifting/lowering station anchor, which is normally connected to a winch-and-pulley system, warrants special attention because it must carry nearly the entire tower load when the tilt-up tower is suspended just above the ground. If the anchors do not seem sufficient for the soil conditions, alternative anchoring should be identified and implemented before tower installation.

Figure 9-6 Example of a screw-in guy-anchor installation. (Source: AWS Truepower)

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 to local regulations. If animals graze near the site, a fence may be necessary to protect the guy stations and tower.

9.7 SENSOR AND EQUIPMENT INSTALLATION

Sensors and other equipment should be mounted in a manner that conforms to the design of the wind measurement programme. Specifications to be followed in the field include monitoring heights, boom orientations, and standoff distances.

Sensor Installation Guidelines

Regardless of the technical solution chosen to support the sensors and the mounting boom design, mounting boom and sensor installation is critical to the success of the wind resource assessment campaign.

It is important to remind the crew that meteorological equipment is fragile and requires careful handling. The moment when sensors are most likely to be damaged is during installation, so proper handling procedures must be followed. Also, keep in mind that sensors mounted on towers will be subjected to wind-induced vibration, so it is important to make sure that locking nuts are used to secure the equipment.

Improper installation can also affect the accuracy of wind speed and direction measurements. In particular, the stub mast supporting the anemometers should be perfectly vertical. One way to achieve this with a tubular tilt-up tower is to use a boom designed by the sensor or tower manufacturer. For a guyed lattice tower, it is preferable to use square-section mounting booms, which are less prone to rotating around their main axis once installed. If tubular horizontal mounting booms are attached to the tower legs using U-clamps, it is recommended to find a way (such as cotter pins or grooves) to keep them from rotating. Rotation results in the anemometer leaning off vertical, resulting in inaccurate wind speed measurements.

Care must also be taken with direction vanes to ensure an accurate direction reading relative to true or magnetic north. Ideally, the wind vane deadband (the point in its rotation where the direction readings are unusable) should be aimed towards the tower. Not only does this orientation 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 vane orientation should be secured in its correct position by placing a cotter pin through the mounting boom and the wind vane. Most manufacturers deliver mounting booms and vanes ready for the placement of the cotter pin, but if the booms are manufactured or sourced independently, it should be included in the equipment design, if possible.

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.

With tilt-up towers (tubular and lattice), the sensors and booms are mounted while the tower is on the ground or suspended just above it. This is the only way to install the equipment, since tubular towers cannot be climbed. By doing so, the sensor heights are easy to set and control, but setting boom directions is harder, and cannot be verified until the tower is raised. If (following the recommendations of the previous section) the tower is raised into the prevailing wind, when the tower is laid flat the booms should stick up at an angle between 45 and 60 degrees on either side of the tower. If the tower is a lattice structure, the boom orientation will be defined by the tower faces.

Fixed lattice 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 should ideally be calm. Strong wind can make it difficult to raise mounting hardware and can increase the chance for the sensors to be damaged when the equipment is raised. In cold, windy weather, tasks involving manual dexterity can become difficult, and there is a danger of frostbite.

Note that adding support booms for anemometers and other instruments on existing towers 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.

Temperature Sensor

A shielded temperature sensor should be mounted on a horizontal boom at least one tower diameter from the tower face to minimise the tower's influence on air temperature. The temperature sensor location should be determined by considering the following factors:

- good exposure to the prevailing winds to ensure adequate ventilation at most times, and
- limited exposure to direct sun (north of the tower in the northern hemisphere and south of the tower in the southern hemisphere) to limit heating from direct solar gain and to reduce the influence of thermal radiation from the tower's surface.

When a set of paired temperature sensors are being used (for delta-T measurements, for example), both sensors should be oriented in the same direction and with the same standoff distance to ensure that they are exposed to similar conditions.

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 in the northern hemisphere and the north in the southern hemisphere 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 minimise 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[12]

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. However, different monitoring areas may have different requirements. Sites prone to lightning activity require an especially 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.[13] Even with complete protection, it cannot be guaranteed that equipment will survive a direct lightning strike.

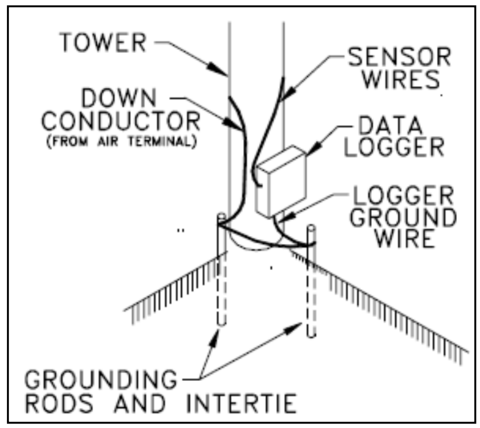

Figure 9-7 Single-point grounding system.

Basic Guidelines

The single-point grounding system shown in Figure 9-7 is the recommended configuration. This setup minimises the potential for developing an offset voltage by a grounding loop. In this system, the down conductor wire (AWG 10 gauge or less – approx. 2.5 mm copper wire) 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, as it may not be able to handle the current produced by a direct lightning strike. 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.

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

[13] Lightning density maps for the world. can be found at: http://geology.com/articles/lightning-map.shtml

Typically, the grounding rod, ring and plates are copper-based to provide a low resistivity for charge dissipation.

The dimensions of the grounding instrument will determine the surface area in contact 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 mm (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 and clearly marked with orange flags to prevent accidents (tripping while walking around the tower or of damaging a vehicle parked near the tower). It is often recommended to put the ground rods within the fence surrounding the tower base.

It is helpful to know the resistivity of the soil to select the proper grounding system. The resistivity is the electrical resistance to current flow within a unit volume of soil, usually near the 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 soil, the better the grounding it will provide. Soils with low resistivity (*e.g.* moist dirt) quickly dissipate any voltage potential that 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 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 – approx. 2.5 mm), non-insulated copper wire referred to as the "down conductor" tied to the earth ground (a grounding rod or buried loop). Any country-specific height restrictions defining the need for obstruction lighting usually refer to the total structure height, which includes the top of the lightning rod.

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. The soil's conducting properties generally improve with increasing depth, additional contact surface area is gained. Rods that fit together to reach greater soil depths may be locally 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 reducing the wire's gauge (which increases its cross-sectional area)
- The down conductor can be secured to the tower's metal surface with band clamps (one per tower section). Deoxidising 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.

The general installation steps for a sodar or a lidar unit are described at the end of this chapter, along with the equipment requirements.

9.8 SITE SECURITY

Wind monitoring systems of all kinds are vulnerable to vandalism and theft. Local residents may find them a nuisance, or object to plans to build a wind project at the site. The cups on cup anemometers are sometimes used for shooting practice, and equipment mounted near the ground, such as solar panels, data loggers, or the grounding system, may be stolen. Companies have even been known to sabotage the measurement equipment of their competitors.

Where vandalism is a concern, both preventive and protective measures can be taken. One preventive measure is to engage the support of the local community for the wind project. Communities that see a benefit – financial or otherwise – from the project are less likely to tolerate vandalism in their midst. Some of the potential financial benefits include the payments received by landowners for the use of their land, opportunities for local firms to build and install towers, and employment opportunities for local residents to provide security, check on equipment, and perform basic maintenance and data collection.

Communities can also benefit from the transfer of skills and knowledge. For example, the science and engineering programmes of local universities are often a source of technically skilled staff. Once trained in methods of resource assessment, they can train others. In addition, the skills needed to build and erect lattice towers and instrument mounting equipment are easily learnt by firms that already supply radio and cell towers. Such knowledge transfer helps foster a sustainable wind energy programme that will reduce costs and logistical hurdles for future projects, and provides a benefit to the local community.

A variety of protective measures can also be taken. For example:

- Install a fence around the base of the tower, and possibly the guy wire anchors as well. Aside from hindering vandals and thieves, fencing can protect against animals which sometimes rub up against, chew, or otherwise damage equipment.
- If frequent manual data retrieval is not required, mount the base equipment (logger and peripherals) high enough on the tower to be out of easy reach.
- Hire security guards, or arrange for local residents, police, or others to stop by the site periodically.

9.9 SITE COMMISSIONING

Site commissioning is the final stage when the measurement system is reviewed and confirmed to be properly installed. 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.

9.10 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, if possible. Typically, coordinates should be expressed to an accuracy of less than 0.01 minute of latitude and longitude (about 10 m) 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.

9.11 POINTS TO REMEMBER

- Measurement system installations must be thoroughly planned, including the following:
    - Equipment procurement
    - Acceptance testing and preparation for deployment
    - Field deployment preparation
    - Installation and commissioning
- Health and safety considerations are crucial for every step of the process.
- The project manager needs to be experienced for the installation to be successful.
- Clear, thorough and accurate installation and commissioning documentation is critical so that data analysis can be performed remotely in the most reliable way.

9.12 SAMPLE SITE INFORMATION LOG

Form Revision Date:

Form Filled Out by:

Site Description	
Site Designation	
Location	
Elevation	
Installation/ Commission Date	
Commission Time (Local or GMT)	
Time Zone – (Daylight Saving Time – if applicable)*	
Soil Type	
Surroundings Description	
Prevailing Wind Direction	(Due True North (TN) /Due Magnetic North (MN))
Magnetic Declination (TN vs. MN)	

*Logger should never be programmed in Daylight Savings Time; local standard time is recommended.

Site Equipment List						
Anemometer Description	Mounting Height	Serial Number	Sensor Slope	Sensor Offset	Logger Terminal Number	Boom Direction (TN/ MN)
Wind Vane Description	Mounting Height	Serial Number	Offset (vane deadband - TN/MN)	Logger Terminal Number	Boom Direction (TN/MN)	
Sensor Description	Mounting Height	Serial Number	Sensor Slope	Sensor Offset	Logger Terminal Number	Boom Direction (TN/MN)

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

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

9.13 MAIN INSTALLATION STEPS FOR TOWERS AND REMOTE SENSING SYSTEMS

TILT-UP TUBULAR TOWERS

Task	Description	Equipment Required (in addition to safety equipment)
1	Layout construction area and tower erection site	GPS, compass, millimetres measurement devices, stakes or other marking devices
2	Clear the area of brush or trees if needed	Chainsaw, clippers, etc.
3	Mark the accurate location of the anchors	GPS, compass, millimetres measurement devices, stakes or other marking devices
4	Install the anchors Commission and test the anchor installation	Anchors will be site specific, from screw-in anchors that can be driven using a skidsteer to concrete anchors or deadman type anchors that may require the use of a backhoe loader
5	Lay out the tower base, the tower elements, the gin pole, tie the guy wires from their respective anchors to their attachment points, following the manufacturer recommendations	Wrenches that are adapted to the provided hardware (guy clamps)
6	With an emphasis on team safety, start raising the ginpole. Once the ginpole is up, start putting the tower under tension to ensure that all the sections slide/adjust to their respective places. The tower should not be raised more than a few inches from the ground, only enough to put all the ginpole and tower lifting wires and anchors in tension, and to verify that they will sustain the loads during erection. Be aware that this is when the tower base is most likely to slip toward the ginpole anchors. The tower may then be lowered, allowing enough space under the tower to install the equipment	Appropriate winch (per tower manufacturer's requirements,
7	Install the grounding rod, the grounding cable along the tower, the mounting booms, the sensors, the wiring for each sensor along the tower, Avoid flapping wires by properly wrapping the wire bundle along the tower in an "helicoid" manner, with about one full turn around the tower for every 2 m (6 ft.). Protect the sensor wires at the tower section joins by using electrical tape or cut-up watering hose.	Wrenches adapted to the provided hardware, silicon to protect electrical contacts at the base of the sensors from corrosion, UV resistant electrical tape to hold the sensor wires along the tower, pre-cut 25 cm (10") sections of watering hose to protect the sensor wire bundles at tower section joins.

8	Install the data logger in the logger box at the tower base, ground the logger per manufacturer's specifications (which include driving one or more copper rods into the ground and wiring them to the logger ground), plug the sensor wires according to the predefined channel number orders, and test the logger and sensor following a well-defined testing procedure. Install the power supply to the logger Make sure all wires enter the logger box from the bottom via a drip loop.	Appropriate screwdrivers and wrenches for the provided hardware, silicon to protect electrical contact from corrosion and to ensure water tight logger box entrance point for the wires, UV resistant electrical tape for miscellaneous uses
9	Once sensors and loggers are all in place and testing establishes they are operating correctly, the tower can be raised. The team leader operates the winch and gives orders to the crew to tension or release the tension for certain guy wires to adjust for an imperfect system geometry (anchors and tower base are not all at the same level) Safety is of paramount importance, and the team leader should be clear in his orders. The crew should access the anchors from the outside the area. Once the tower is within 10-15 degrees of vertical, the ginpole weight can suddenly pull the tower to vertical. To avoid this, special attention should be paid to the winch-to-ginpole wire tension, as the tension decreases when getting close to this point, and the guy wires attached to the anchors opposite to the ginpole should be kept shorter to avoid a tower collapse, and should be slowly released in small steps while the ginpole is lowered using the winch. The tower erection step is final once the tower is straight up and all guy wires have the proper tension per manufacturer's specifications.	Every crew member should have appropriate wrenches to adjust the wire length and tension, Communication between the team leader and the crew members is critical during this phase, and a radio can be valuable for ensuring proper communication.
10	Once tower is raised and all guy wires are appropriately tensioned, wire markers should be installed on the lower guy wires, and system commissioning should be performed. If a fence is required, it should be installed before leaving the site.	Wire markers for lower guy wires. GPS, computer, high resolution camera, notebook for system commissioning Fencing hardware with installation equipment

GUYED AND SELF-SUPPORTING LATTICE TOWERS

Task	Description	Equipment Required (in addition to safety equipment)
1	Lay out construction area and tower erection site	GPS, compass, millimetres measurement devices, stakes or other marking devices
2	Clear the area of brush or trees if needed	Chainsaw, hand clippers, etc.
3	Mark the location of the anchors and tower base	GPS, compass, millimetres measurement devices, stakes or other marking devices
4	Install the anchors Commission and test the anchor installation Pour the tower base if concrete foundation is required.	Anchors will be site specific, from screw-in anchors that can be driven using a skidsteer to concrete anchors or deadman type anchors that may require the use of a backhoe loader
5	If tower is to be assembled on the ground and then raised using a crane, lay out the tower sections near the tower base and assemble the tower sections, tie the guy wires to their attachment points following the manufacturer recommendation.	Wrenches that are adapted to the provided hardware (nuts and bolts with torque requirement)
6	With emphasis on the crew's safety, raise the tower. If tower is to be raised in one piece using a crane, the crane shall be attached to the tower in the upper portion of the tower (above its centre of gravity) and should not detached until the tower is vertical and all guy wires are in place and appropriately tensioned. If tower is to be stacked in place using a winch and jib pole system, prepare the assembly on the ground by laying out the equipment to be raised so that stacking and assembly is as safe and efficient as possible. Each time guy wires are supposed to be attached to the new tower section, ensure that the bottom part of the tower is vertical and the guy wires are appropriately tensioned.	Appropriate tools (per tower manufacturer's requirements) Crane or winch and jib pole system depending on chosen solution

7	Install the grounding rod, the grounding cable along the tower, the mounting booms, the sensors, the wiring for each sensor along the tower, Make sure to avoid wire flapping by properly tying the wire bundle along the tower leg. Make sure to protect the sensor wires at tower section changes by using electrical tape or cut-up watering hose as protection.	Wrenches adapted to the provided hardware, silicon to protect electrical contact at the base of the sensors from corrosion, UV resistant electrical tape to hold the sensor wires along the tower, pre-cut 25 cm (10") sections of watering hose to protect the sensor wires bundle at tower section changes
8	Install the data logger in the logger box at the tower base, ground the logger per manufacturer's specifications (which include driving one or more copper rods into the grounds and wiring them to the logger ground), plug the sensor wires according to the predefined channel number orders, and test the logger and sensor following a well-defined testing procedure. Connect the power supply to the logger. Make sure all wires enter the logger box from the bottom via a drip loop.	Appropriate screw drivers and wrenches for the provided hardware, silicon to protect electrical contact from corrosion and to ensure water tight logger box entrance point for the wires, UV resistant electrical tape for miscellaneous uses,
9	Once tower is raised and all guy wires are appropriately tensioned, wire markers should be installed on the lower guy wires to avoid accidents, and system commissioning should be performed. If fence is required, it should be installed before leaving the site.	Wire markers for lower guy wires. GPS, computer, High Resolution Camera, Notebook for system commissioning Fencing hardware with installation equipment

REMOTE-SENSING SYSTEMS

Task	Description	Equipment Required (in addition to safety equipment)
1	Clear the area of brush or trees if needed	Chainsaw, hand clippers, etc.
2	Mark the accurate location of the remote sensing unit. Ensure that trees or buildings are outside the perimeter defined by the equipment manufacturing to avoid echo (mostly for sodar)	GPS, compass, millimetres measurement devices, stakes or other marking devices
3	Pick a location that will be flat enough to properly level the remote sensing unit with ease. Lay wood planks on the ground where the remote sensing unit legs are expected to touch the ground so that the unit points in the right direction.	Level, compass, Wood planks
4	Install the remote sensing unit, ensure that it's levelled, pointing in the right direction, ensure that the legs are on wood planks or on hard ground in a manner that will preclude them from sinking into the ground over time and lead to the unit to become unlevelled Anchor the unit if harsh conditions are expected and wind can move the unit, or for security reasons	Screw in anchors or other anchoring technology as appropriate Locks
5	Install on the ground or on wood planks the power supply unit near the remote sensor unit and plug it. Anchor the power supply unit as needed.	Wood planks, electrical tape Screw in anchors or other anchoring technology as appropriate Locks
6	Start the power supply unit, start the remote sensing unit, commission the system. If fence is required, it should be installed before leaving the site.	GPS, computer, High Resolution Camera, Notebook for system commissioning Fencing hardware with installation equipment

10 STATION OPERATION AND MAINTENANCE

The goal of the operation and maintenance phase is to ensure the reliable operation of the measurement systems throughout the wind monitoring programme. 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 needs to be developed. It should incorporate various quality assurance measures and provides procedural guidelines for all programme personnel. 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 programme are provided in this chapter.

Although a sound operation and maintenance plan is critical, ultimately the success of the programme depends on the field personnel. They must be thoroughly trained in all aspects of the programme, 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.

10.1 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 frequently (daily or weekly), 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 three 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 programme to attain the recommended target of at least 90% data recovery. The data retrieval process is detailed in Chapter 11.

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. To minimise potential data loss, such visits should be carried out as soon as possible after a problem is suspected. Both the programme budget and staffing plans should anticipate at least one unscheduled site visit each year.

10.2 OPERATION AND MAINTENANCE PROCEDURES

The operation and maintenance programme should be documented in a manual. The goal of this 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.

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 stub masts 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 sections 11.3 and 12.2).
- Wind vanes and anemometers should be replaced on a regular basis as part of a preventive maintenance plan. A replacement schedule that minimises 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 check 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 sample Site Visit Checklist at the end of this chapter 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; tilting up or down a tubular tower can require five or more.
- 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 minimise 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-based 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 email 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.

10.3 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 standardised 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.

10.4 SPARE PARTS INVENTORY

The operation and maintenance plan must anticipate equipment malfunction and breakage. To minimise 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 (*i.e.* those mounted high on the tower) necessary to replace any broken or malfunctioning items, 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 three monitoring towers should have a parts inventory sufficient to outfit a complete tower. For networks of several towers, 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, as these are exposed to the wind.
- 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 programme 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 shooting 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.

10.5 POINTS TO REMEMBER

- The way the measurement systems are operated and maintained will greatly impact the success of wind resource measurement campaign.
- To be effective, the operation and maintenance programme should be documented in an Operation and Maintenance Manual.
- The Operation and Maintenance Manual should include scheduled site visits to perform routine, preventive maintenance on the physical structure and visually check the instruments and other components.
- The Operation and Maintenance Manual should also prepare the team to react to unplanned events and performed unscheduled maintenance tasks.
- As for the installation of the systems, the health and safety of the field crew should receive priority at every step of the process.
- Clear, thorough, and accurate documentation of every performed operation and maintenance task is crucial to the programme success.

10.6 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, tape, 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?

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:

____

____

____

____

____

____

____

11 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. A further aim is to allow frequent review of the data so that problems with the measurement equipment can be quickly flagged and addressed. This chapter highlights the key aspects of meeting these objectives, including data retrieval, protection, and documentation.

11.1 ON-SITE DATA STORAGE

Every data logger has a storage device inside or attached to the unit. (See Table 7-5 for a list of the main types of storage device.) Data are typically stored in this device 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*.

The raw data are the basic currency of resource assessment. It is essential that they be preserved and protected as an original record of the measurements that were taken. This will not only help avoid errors, it will support the financing of the wind project by giving outside reviewers' confidence that the measurements were properly recorded and have not been tampered with.

Understanding how the logger stores the data (described in section 7.4) and verifying that various parameters such as time stamps and transfer functions are properly entered are therefore key to the integrity of the wind measurement programme.

Time Settings

Regardless of system type, data recording should be serial and all records marked by a time and date stamp. The time zone programmed into the equipment must be clearly indicated and recorded at the time of installation to allow for proper interpretation of the collected data; the time zone offset relative to GMT (UTC) must be indicated. Furthermore, the logger should be programmed to record times in local standard time (LST) rather than daylight savings time (DST). These are standard functions for wind energy applications, and all equipment should be programmed accordingly before installation, if possible.

For systems requiring manual data retrieval, clock settings should be verified at installation and at each subsequent site visit. If swapping data cards, the exact times of removal of the original card and installation of the new one should be documented to allow for later inspection and verification during processing. If not swapping data cards, the logger time should be confirmed to be within an acceptable margin of error from the actual time (for example, if recording at 10-minute intervals, a difference of less than ten minutes would be acceptable). If outside of the accepted margin, adjustments should be made to the logger clock and clearly documented.

Finally, care should be exercised when interfacing with the unit via a laptop computer or other device having its own time setting to ensure that the logger retains its correct programming.

For some system types equipped with remote communications, time settings can be examined and changed remotely. Two main options exist (with slight variations between manufacturers and equipment types) - time synchronisation with the central computer the equipment communicates with, and synchronisation with an Internet-based time server. In either case, care must be taken to ensure the time is set to correct LST.

Proper documentation of both pre-deployment and any in-field adjustments to time settings is required to aid in the processing and interpretation of the collected data. Furthermore, if multiple on-site measurement platforms are present, it is important to synchronise their time settings as closely as possible in the raw data. Adjustments can be made to time settings during post-processing, but the data analysis procedure can be simplified considerably if all collected data are consistent.

11.2 DATA RETRIEVAL

Storage Capacity

Two constraints determine how often the data should be retrieved. The first is how long the logger can accumulate data before it reaches its capacity and data losses start to occur. Manufacturers usually provide tables or methods to calculate the approximate available storage capacity (in days) for various memory configurations. Using this information, you should satisfy yourself that the storage capacity is large enough that under your data retrieval plan there will never be an occasion when the storage becomes full.

Table 11-1 provides rough estimates of the storage capacity for standard data card sizes, different numbers and types of sensors, and different recording intervals. The values represent the approximate number of days of data that can be stored with a payload (total number of sensors attached to the logger) of 6 sensors. They assume a daily file size for 10 minute data of 18.6 KB. Actual values will vary depending on logger type; for example, some loggers have a standard file size regardless of number of measurements, while the file size of other types increases in proportion to the number of sensors installed.

Based on the assumptions behind this table, with the standard 10-minute data recording interval, a logger equipped with even a 2 MB card should have enough storage capacity for 214 days, or around 7 months. With a 16 MB card, the data storage capacity is 1720 days, or nearly 5 years. If the data are being collected at 1-minute intervals, however, then the same 16 MB data card can hold about 172 days, or nearly 6 months. Collecting at 3 second intervals implies the same card can hold only about 8.6 days of data.

Storage requirements are generally greater for remote-sensing systems than for towers due to the number of vertical levels recorded and the supplemental data that are usually collected (*e.g.* data quality information such as signal-to-noise ratio and meteorological data such as precipitation and temperature). Many systems are provided with hard drives, laptop computers, or a combination of these, to handle both storage and processing needs. However, unlike the chips and cards installed in many data loggers, these media cannot be easily swapped out, and therefore it is usually necessary to access the data remotely.

Table 11-1. Approximate data storage capacity of common media, in days, assuming a total of 6 sensors (*e.g.* 3 anemometers, 2 direction vanes, and 1 temperature sensor).(Source: AWS Truepower)

Card Size	Recording Interval			
	3 second	1 minute	10 minute	1 hour
2MB	1	20	214	1284
5MB	2.6	52	536	3216
8MB	4.2	86	860	5160
16MB	8.6	172	1720	10,320
32MB	17.2	344	3440	20,640
64MB	34.4	688	6880	41,280

Achieving High Data Quality and Recovery

The second – and usually more important – factor determining the data retrieval frequency is the need to maintain high data quality and minimise data losses. Unless you retrieve and examine the data, you cannot tell if the equipment is operating correctly. Thus, frequent data retrieval is an essential part of the overall operations and maintenance strategy.

How frequent? With remote data transfer, a daily schedule is usually best. Besides allowing frequent data checks, it offers the additional benefit that it keeps the amount of data to be transferred each time compared to a longer interval relatively small. This is especially important for remote-sensing systems, which generate much more data than tower systems. Even with towers, however, a daily schedule may be helpful with slow or weak cellular data connections. A retrieval every two or three days to once a week is also acceptable, if the remote connection can handle the larger data transfer. This may be desirable in areas where communications are expensive or on-site power budgets are low.

With manual data retrieval, the desire to retrieve data as often as possible must be weighed against the time and cost to visit the site. A weekly schedule often strikes a good balance between these priorities. For intervals greater than two weeks, the risk of serious data loss grows to an unacceptable level. Consider a monthly schedule as an example. If the logger fails right after one visit, then the failure will not be discovered for 30 days, until the next visit. Suppose it takes two weeks to obtain and install a replacement logger. The resulting 6 week data loss represents around 12% of a year's data. With this one event the data recovery for the year would fall below the 90% target.

Situations can arise that warrant unscheduled transfers. For example, if sensor irregularities are discovered when the data are reviewed, a follow-up transfer might be called for to see if the problem persists. An awareness of icing or severe weather at the site might prompt a 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.

Manual Data Transfers

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

- First, 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.
- Second, the collected data are transferred to a central computer where the data are analysed and backed up.

Exceptional care should be taken in handling the data cards and field laptops, as once the data are wiped from the logger, they are the only record of the sensor measurements. Training should be provided on proper handling of the storage equipment, such as avoiding static discharge. Immediately before and after the cards are swapped, the technician should verify that the data logger is functioning correctly. Additional guidance on data handling and protection is provided in section 8.4.

Remote Data Transfers

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 programmes 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. The phone home method relies on the device to independently verify its settings, and requires care and proper programming up front to ensure no incorrect or inconsistent changes to the configuration. 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 utilises 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.

Network Reliability and Speed

The availability, reliability, and speed of wireless or satellite data transfer networks may be limited in island environments. Fortunately, file sizes of commonly collected parameters (such as 10-minute wind speed, direction, and temperature) are quite small and can be transferred relatively quickly and inexpensively, even for several days at a time.

However, at sites with larger volumes of data to be transferred, or when multiple monitoring sites are present, network reliability, and potentially speed, can become a concern. In such situations, it is important to check promptly that the data have been properly received and are uncorrupted. In addition, it may be prudent to store high-volume data on-site until they can be retrieved manually, and to transfer only files of small size (*e.g.* 10-minute data) over the remote connection. The remote transfer will allow the health of the system to be monitored, while avoiding the danger of losing data over an unreliable network.

Power Supply Considerations

Different types of remote data transfer equipment vary in their power requirements. The largest drivers of power usage are the equipment uptime and data transfer intervals.

Where power supply is limited, it makes sense to adopt a power-conserving data transfer strategy. This can be done in two ways. First, equipment uptime and transmission time of day can often be configured to conserve power. For example, a modem can be turned off during all but a few hours of the day, and transmissions can be scheduled for when solar batteries are likely to be fully charged.

Second, the data transfer interval (the number of days between transfers) can be adjusted both to increase battery life and to reduce data transfer costs. At sites with less reliable communications, repeated retries, dropped connections, and interrupted data transfers can all consume power and increase data-transmission costs. Making such transfers on a daily basis may not be sustainable in that case. However, if the system is programmed to call, for example, only once every four days, the transmission airtime and power usage may be cut substantially. (The total airtime tends to go down with less frequent calls because the time needed to send even several daily files is often less than the time to connect to the network.) You should experiment with different call strategies until you find one that works.

11.3 DATA QC

A critical component of a monitoring programme is timely notification of equipment status and failures. This allows for the highest data recovery rates possible, assuming problems are addressed promptly. Detection of equipment problems is accomplished both through site visits and frequent review and quality control (QC) of the data collected.

Every visit to the site provides an opportunity to verify visually the instrument and tower status. Some tower or sensor problems (such as bent booms, a leaning or bending tower, or loose wires) are difficult to identify or diagnose based strictly on an inspection of the data, but can be spotted quickly when on-site. Many data loggers also offer the option to manually interface on-site to view instantaneous sensor readings or other important items such as battery voltages. If problems are identified, this should allow for preventative maintenance or proper diagnosis and planning to occur immediately.

Once the data have been collected (either manually or remotely), they should be screened for signs of problems such as logger and sensor failures and data transmission failures. This QC process should be done on a weekly or biweekly basis, or more often, depending on the frequency of retrieval or when significant weather events are expected to have impacted the tower. If the data are obtained in their raw (binary) format, preliminary inspection and screening can often be accomplished via the data conversion software provided by the equipment manufacturer. For some data types, conversion to text (ASCII) files may first need to occur. The following provides a basic procedure.

First, you should ensure that all raw files that you expect have been delivered or downloaded. If the logger is expected to deliver raw data files in sequential order, check that that every file has been received in the proper sequence. An occasional gap might be normal, but sustained periods of inconsistent data recovery may indicate communications or equipment problems.

Second, for tall towers, check the anemometers, wind vanes, temperature, and voltage data since the last collection or screening date and look for gaps or strange data. This can be done by creating simple line charts and scatter plots in a spreadsheet programme, data analysis software (such as Windographer), or a web-based data visualisation tool. Compare like sensors to each other – anemometers to anemometers, direction vanes to direction vanes. Under normal conditions, anemometers at the same height should differ from each other by no more than a few percent (except when one is in the tower shadow). Direction vanes should differ by no more than around 10 degrees. A scatter plot comparing the 10-minute records of anemometers is a useful tool for spotting suspicious behaviour, such as an anemometer that is slowing down excessively at low speeds. Any suspect behaviour should be flagged, and a decision made whether to visit the site to investigate further.

For most remote sensing units, diagnostic indicators are included in the units' programming to assess the quality of the collected data and any issues. Therefore, a verification of proper communication will suffice for the initial QC steps. Details on data validation are provided in Chapter 12.

11.4 DATA PROTECTION AND ARCHIVING

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

Physical and Electronic Protection

Both physical and electronic methods of protecting data are recommended. Physical protection begins with site security and proper installation of the data logger on the tower; see Chapter 7. In regions where there is opposition to wind energy – or competition for wind energy sites – such measures are important to discourage theft or vandalism, which could result in a significant loss of data.

A personal computer is usually the primary location of the working database, so care should be taken to ensure that the computer is password-protected and kept in a secure location, that its hard drives are in good working order, and that the data are frequently backed up. If a laptop is taken into the field for data retrieval, its data should be backed up to a desktop computer as soon as possible after data have been retrieved. This can be done by as simple an expedient as sending the files to yourself as an attachment to an email, or through an online backup service.

Careful handling should likewise be observed for all other data storage media. Data cards and hard disk drives should be protected from static charge, magnetic fields, and temperature extremes.

Many equipment manufacturers offer additional electronic protection measures. The first and most basic of these is the binary format of many files stored on the logger data cards. Although not impervious to a determined hacker, this format will defeat casual attempts to access the data. In addition, some logger manufacturers offer encryption of the data recorded in the logger memory with numerical codes or text strings. The proper key(s) must be used in the data conversion and analysis software to allow the data to be understood.

Finally, some manufacturers offering remote data retrieval require authentication to access the data. This could be in the form of requiring a password or using secure file transfer protocol (sFTP) transfer protocols.

Data Handling

Improper data handling greatly increases the risk of data loss. All personnel in contact with the data and storage media should be fully trained and understand the logger hardware, data retrieval software, and computer operating system. Technicians should be aware of all instances in which data can be accidentally overwritten or erased.

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, and preferably 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. Many such online options can be automated to both simplify local backup and make the files instantly accessible to off-site stakeholders.

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

Data Inventory

You should periodically take an inventory of all collected raw data files to ensure the data are complete. Short gaps in the record occasional occur, but frequent or longer gaps pose a threat to the success of the resource measurement programme.

It is not uncommon for sites relying on remote data transfer to occasionally skip a file or lose a few records due to an interruption in communications. Fortunately, when this occurs the gaps on the remote computer can usually be filled by retrieving the logger's data card. With manual data retrieval, gaps should not occur unless a card is corrupted or lost or damaged in transit.

11.5 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.

11.6 POINTS TO REMEMBER

- Data logger configuration, storage, and retrieval protocols must be carefully implemented and documented to ensure the highest possible data recovery and ease of data interpretation.
- Frequent review of recorded data should be conducted to diagnose sensor, logger, or tower problems and to implement corrective action as quickly as possible.
- Proper data collection, handling, and storage protocols should be implemented to ensure high data recovery and asset protection; documentation should be prepared at all steps.

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		

12 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 high quality data are used in subsequent analyses and that the data are as accurate as possible. Basic QC, which refers to the initial screening of data for obvious problems, is often done as part of the data retrieval and process (described in the previous chapter), and is performed more frequently than data validation, which represents a more detailed inspection of the data to identify invalid or suspect values. A full data validation is typically done on a quarterly or annual basis, or when the measurement programme reaches a significant milestone.

Validation means, generally, the inspection of data for completeness and reasonableness, and specifically the detection and flagging of bad (invalid, suspect, and missing) 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 minimise both types of error. Equipment manufacturers, experienced users, and consultants can be consulted for guidance in developing and implementing such a process.

In this section, techniques appropriate for both QC and validation of tower data will be covered under the validation process. The validation of remotely sensed data is a more specialised topic, and methods depend largely on the specific model chosen and the environmental conditions of the chosen site. If you are using a remote sensing system, you should work with the equipment manufacturers or an experienced consultant to develop an appropriate data validation procedure

12.1 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, Renewable 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 characterising 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.

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 to avoid inadvertently corrupting or overwriting the original 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*.

12.2 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 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 on either prior knowledge or information from other sensors on the same tower. The algorithms commonly include range tests, relational 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. Figure 12-1 illustrates one such example, as

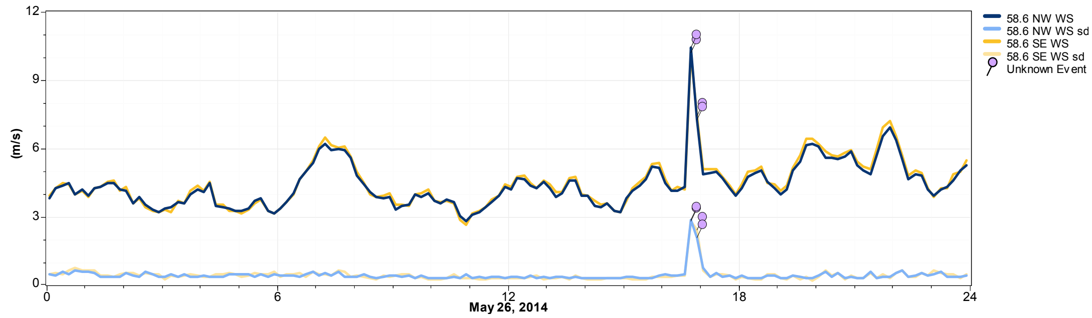

Figure 12-1. Example of an automated screening check. The program flagged a period of high wind speed and high speed standard deviation observed at two sensors at the same height on a mast. In this instance, subsequent examination shows the episode was caused by a passing thunderstorm. (Source: Windographer)

seen in the Windographer software (www.Windographer.com).

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 towards over-detection is that there will be an opportunity to re-examine 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. However, 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: 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. Table 12-1 presents examples of range-test criteria. A reasonable range for 10-minute average wind speeds is from the anemometer offset (0 or a small constant) 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. Note that a variety of voltage measurement systems exist, which are intended to measure different systems (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.

An example of a range test failure is presented in Figure 12-2. In this particular instance, the southwest-facing instrument at 57 m height (57 SW WS) was hit by lightning, which caused the instrument to malfunction afterward, as indicated by the “Suspect” flag.

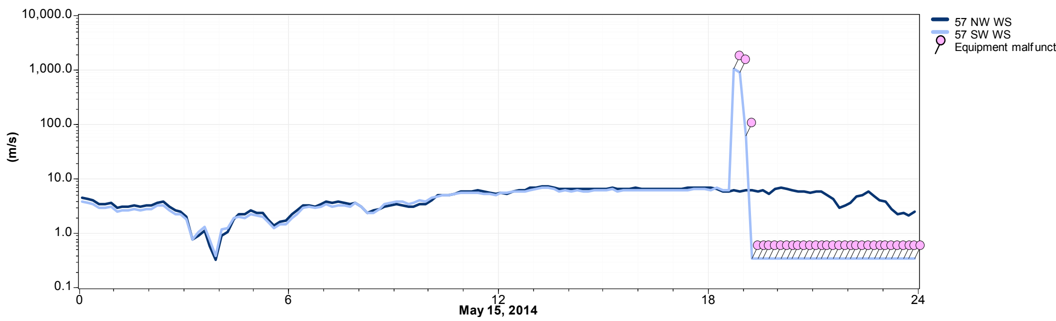

Figure 12-2. Range test failure example. The large spike in observed speed to an unrealistic value signals a sensor failure, in this case caused by a lightning strike. (Source: Windographer)

Relational Tests: 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 tower shadow); wind shears between heights should fall within reasonable bounds (which may vary diurnally and seasonally). Table 12-2 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.

Table 12-1 Example range test criteria

Sample Parameter*	Validation Criteria
Horizontal Wind Speed	
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
Vertical Wind Speed	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

An example of a common relational test failure from a spreadsheet analysis is presented in Error! Reference source not found.. The northwest anemometer (58.6 NW) reads more than 0.5 m/s lower than the southeast anemometer at the same height (58.6 SE WS), triggering an "Unknown Event" flag (labelled -990). The records should be examined by the data analyst to determine if either sensor is experiencing a problem.

C	D	E	F	G	H
58.6 NW WS val	58.6 NW WS sd	58.6 NW WS flag	58.6 SE WS val	58.6 SE WS sd	58.6 SE WS flag
9.75	1.17		10.27	1.29	
9.58	1.31		10.08	1.41	
9.54	1.21		10.04	1.33	
9.34	0.89		9.78	0.99	
10.31	1.23	-990	10.82	1.37	
9.79	1.19	-990	10.26	1.31	
10.25	1.14	-990	10.8	1.29	
9.78	1.14	-990	10.26	1.26	
9.57	0.99	-990	10.05	1.07	
10.38	1.88	-990	10.97	2.02	
10.86	1.19	-990	11.45	1.31	
9.94	1.19		10.46	1.28	
10.95	1.34		11.58	1.46	
12.03	1.37	-990	12.64	1.44	
11.38	0.99		12.03	1.09	
11.05	0.88	-990	11.68	0.98	
10.02	1.15	-990	10.55	1.28	
9.34	1		9.78	1.07	
8.91	1.14		9.37	1.21	
9.48	1.02		9.97	1.1	
8.74	0.79		9.17	0.83	
7.73	0.81		8.14	0.86	
8.22	0.74		8.65	0.73	

Figure 12-3 – Relational test failure example

Table 12-2 Example relational test criteria.

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 < α** < 0.45
* All monitoring levels except where noted ** α = wind shear exponent	

Trend Tests: These checks are based on the rate of change in a value over time. Table 12-3 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.

The examples of validation criteria in Table 12-1, 12-2, and 12-3 are not exhaustive, nor do they necessarily apply to all sites. With experience, you 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: When an anemometer is downwind of the tower, it is said to be in the tower's shadow. 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, the anemometer would be in shadow for wind directions ranging from 240 degrees to 300 degrees. The shadowed region may be different for a lattice tower because the boom is typically offset from the centre 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 12-4 presents two types of ratio plot, which are helpful for determining angles of tower shadow and confirming the proper functioning of anemometers. Figure 12-5 illustrates a tower shadow event in a time series plot.

Table 12-3 Example trend test criteria

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	

Icing: Icing events are usually flagged when the standard deviation recorded by the direction vanes is zero or near zero and the air 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 ice accumulation. The exception to these rules is heated instrumentation, which can be very valuable in identifying icing. Severe icing may also cause other tower or sensor problems that can only be diagnosed during a site visit. The tower in Figure 12-6 obviously has a big problem, though it may not trigger any concerns in the data validation. Figure 12-7 presents an example of sensor icing, also in time series format.

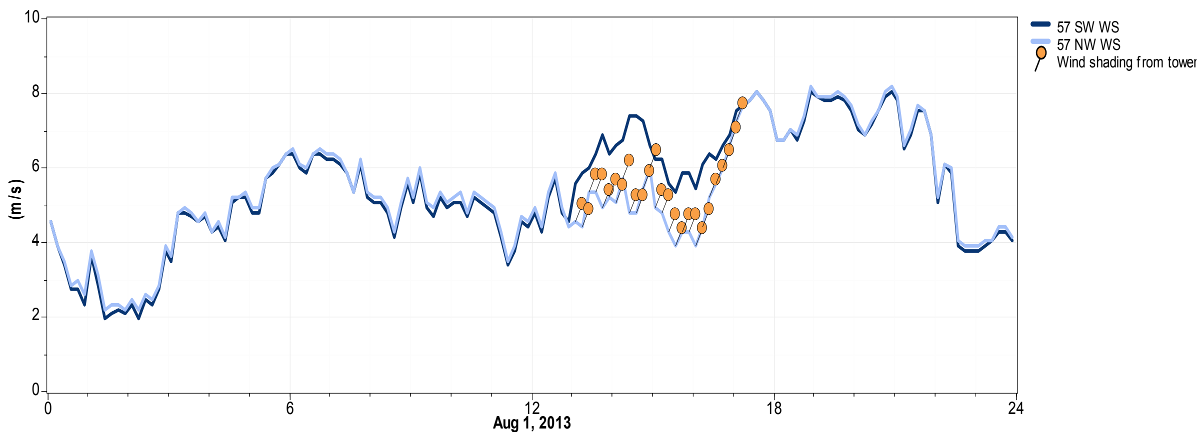

Figure 12-5 shows the effect of tower shadow in a time series. In this case, the northwest sensor reads much lower than the southwest sensor, and so receives the tower shadow flag.
(Source: Windographer)

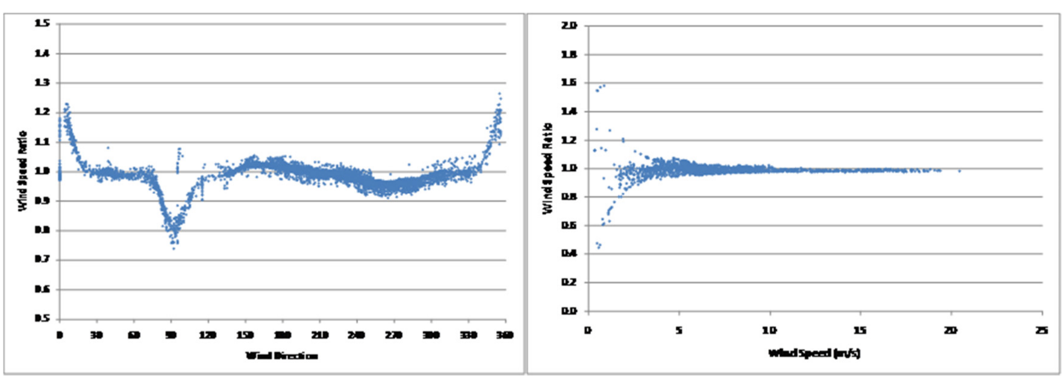

Figure 12-4 Scatter plots of the speed ratio for a pair of anemometers at the same height as a function of wind direction (left) and wind speed (right). The tower shadow zone is clear evident on the left, centered on due north (0 degrees), when the south-facing sensor is in shadow, and due east (90 degrees), when the west-facing sensor is in shadow. The right-hand plot confirms that the sensors behave consistently for speeds above about 4 m/s, the threshold of interest for wind energy.
(Source: AWS Truepower)

Figure 12-6 Tower failure caused by heavy icing. (Source: AWS Truepower)

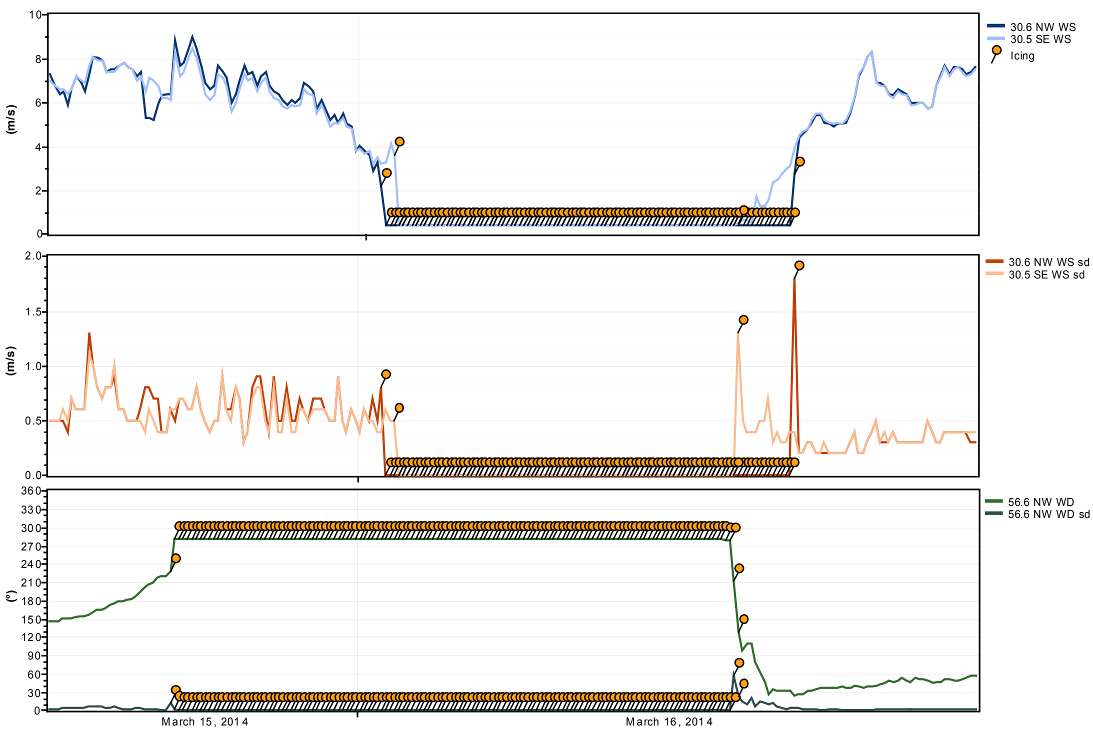

Figure 12-7. Sensor icing example. The wind speed and direction standard deviations are very small or zero, while temperature data (not shown) indicate below-freezing conditions, triggering the icing flag. (Source: Windographer)

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.

- 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 signalling an event are crossed. Periods around flagged icing episodes should be scrutinised to be sure the times of onset and conclusion have been accurately identified.

- Assign invalid data a code, or flag, indicating the suspected reason. Table 12-4 gives some examples. The values should be well outside the normal range for all sensors, *e.g.* -990, to avoid possible confusion with valid data. 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

Table 12-4 Example validation codes.

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)

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.

12.3 POST-VALIDATION ADJUSTMENTS

High-quality sensors mounted correctly should provide accurate measurements of wind speed, direction, and other meteorological parameters most of the time. However, 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 to only 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.

Depending on the boom length and tower geometry, these effects can be up to several percent of wind speed, 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 12.4.2

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 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 sensors to account for these tendencies, a more accurate energy production estimate can be obtained.[14]

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.[15]

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. It should also be noted that sonic anemometers may have limitations similar to remote sensing devices in relation to measurements during precipitation. These should generally be identified and removed during the data validation process, but post-validation inspection of the recorded data and its recovery are also beneficial.

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. However, 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,[16] 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 modelling. 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.

12.4 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

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

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

[16] 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.

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 programme 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 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. (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, linear, and consistent over time 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. You 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; ideally before data validation occurs. 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 5 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 characterising 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.

12.5 REMOTE SENSING DATA VALIDATION

The validation of remote sensing data requires the screening of multiple parameters that are either directly measured by the unit or calculated from retrieved data. The device manufacturer or an experienced remote sensing analyst should be consulted to develop a screening plan, or to interpret the built-in screening measures often applied to data of this type. The list below, while certainly not exhaustive, provides several important parameters to review and assess in the context of remote-sensing data validation.

- Quality Factor: An included parameter on several types of remote sensing devices, this provides a measure of the confidence in the recorded data based on criteria selected by the manufacturer. The unit-specific criteria and their application in the quality factor should be well understood before beginning the data validation procedure.
- Vertical Velocity: Extreme vertical velocity records can indicate problems with the measurements, periods of precipitation, or transient events. This parameter can be reviewed on a site-specific basis to determine its valid range.
- Missing Data or Records: While a decrease in data recovery with height (above approximately 100 m) is normal, inconsistent or very poor data recovery at different heights or particularly bad data recovery at one or more heights could be indicative of environmental or hardware issues.
- Comparison with other data: Comparison with other data sources, such as a collocated tall tower or even between different levels of the same remote sensing platform, can provide valuable checks on the recorded data.
- Precipitation: Where possible, a rainfall sensor should be installed along with a remote sensing device, and used to identify or remove potentially suspect periods of data. While the effects 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.
- Signal-to-Noise Ratio (SNR): This is often provided as an indicator of data quality and, once experience has been gained at a site, can aid in data validation.

- Signal Amplitude: Can provide an indication of data quality, and is generally platform-specific.
- Battery Voltage: Can be examined to ensure proper operation of the unit and any impending maintenance needs.
- System Level Indicator: Many systems possess pitch and roll indicators which may alert the user when the system is significantly out of level (thus potentially biasing the wind speed readings). Alternatively, slight deviations from level can be corrected for in post-processing.

12.6 MONITORING PROGRAMME DOCUMENTATION (PROJECT LOG)

Documentation of all adjustments, assumptions, and observations made during the data validation process is extremely valuable, for both end users and those who may obtain the raw data in the future. These same users would benefit from documentation of all tower maintenance, including configuration or instrument changes, data logger changes, and any equipment failures. While this information will likely already be recorded elsewhere, having it in the same location as the validation notes can provide valuable insight into the choices made during validation.

A recommended approach is to create a Project Log containing not just information about the measurement platform data records and validation, but also about their locations and any other pertinent information. An example of this type of document is presented at the end of the chapter, and is recommended to be available to any analysts or stakeholders interested in the details of data processing.

12.7 POINTS TO REMEMBER

- Accurate data conversion is essential in the data analysis process; particular care should be exercised in relation to anemometer transfer functions and wind vane offsets.
- Both preliminary data QC (done regularly) and in-depth data validation (done periodically), are required during the monitoring campaign.
- Recorded meteorological tower data, as well as regional reference sources, provide valuable information as to the tower configuration and what is occurring during the data validation.
- Experienced parties should be consulted to develop data validation routines, particularly for remote sensing devices.

12.8 SAMPLE PROJECT LOG

PROJECT LOG

Project Information:

Project Name:	
Country:	
Location (State/Province):	
Programme Manager:	
Data Analyst:	

Mast Information:

Mast Number	**Period of Record (POR) (mm/dd/yy)**		**Site Audit Date(s) (mm/dd/yy)**	**Anemometer Heights (m)**	**Vane Heights (m)**	**Temp Height (m)**
	Start	**End**				

Data Validation Notes (add paragraph for each additional mast as necessary):

Mast Number (Name)	**Validation Notes**

XXXX (XXX)	• Logger type:
	• Missing data:
	  ○
	• Data adjustments:
	  ○ Vane shifts:
	  ○ Boom shifts:
	  ○ Post-Validation Adjustments (Averaging, Turbulence Intensity, etc.):
	• Maintenance (date/action):
	  ○
	• Failures (sensor/date):
	  ○
	• Notes:

13 WIND RESOURCE REPORTS

Once the data validation is complete, the data can be analysed 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 programme. Software to do this is available from several vendors, including some data logger manufacturers. Customised reports can also be created with spreadsheet and database software.

Wind resource reports can be created any time during the course of a measurement campaign, but are usually done on a regular schedule such as monthly, quarterly, or annually, as well as at the end of the campaign. Naturally, monthly and quarterly reports are usually more cursory, and may consist of just one or two pages of the most critical data. Annual and final reports are more comprehensive, and may be incorporated into a "bankable" energy production report on which project financing will be based.

This chapter describes the parameters usually calculated and summarised in reports, and typical report formats.

13.1 KEY PARAMETERS

Data Recovery

The data recovery (DR) is defined as the number of valid data records – after validation – 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, and should include data substitution and averaging where this has been performed.

The method of calculation is as follows:

$$DR = 100 \times \frac{N_{valid}}{N} (\%) \qquad \text{Equation 13-1}$$

where N_{valid} represents the number of valid records and N the total number of possible records in the period. For example, the total number of possible 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:

$$\mathrm{DR} = 100 \times \left(\frac{4{,}200}{4{,}464}\right) = 94.1\% \qquad \text{Equation 13-2}$$

Data recovery is a key measure of the overall quality of the measurement campaign. If the DR is much less than 90%, then the accuracy of the resource assessment is called into question.

Mean and Annualised Mean Wind Speeds

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

$$\bar{v} = \frac{1}{N_{valid}} \sum_{i=1}^{N_{valid}} v_i \qquad \text{Equation 13-3}$$

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 favour of months with more complete data coverage. In addition, 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.

The *annualised 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 annualised 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:

$$\bar{v} = \frac{1}{365.25} \sum_{m=1}^{12} D_m \overline{v_m} = \frac{1}{365.25} \sum_{m=1}^{12} D_m \left(\frac{1}{N_m} \sum_{i=1}^{N_m} v_{im} \right) \qquad \text{Equation 13-4}$$

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, including leap years). The inner sum is over those speeds that fall within a particular calendar month. The calculation is illustrated in Table 13-1. 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. However, the annualised average is only 7.39 m/s, because the repeated months are windier, on average, than the other months.

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 annualised mean can sometimes be obtained by assuming the missing months are similar to the months immediately before and after.

Table 13-1 Sample monthly data record for a station, illustrating the difference between period of record and annualised mean speeds.

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
Annualised Average			7.39

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Speed Frequency Distribution and Weibull Parameters

The speed frequency distribution is 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 can be stored in a tabular format (by convention called a TAB file), which is used as an input to wind plant design software.

The speed frequency distribution can sometimes be well approximated by a Weibull distribution given by the equation:

$$p(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} e^{-\left(\frac{v}{A}\right)^{k}} \qquad \text{Equation 13-5}$$

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 fitting 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.

Turbulence Intensity

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. Normalising this value with the mean wind speed gives the turbulence intensity (TI):

$$TI = \frac{\sigma}{v} \qquad \text{Equation 13-6}$$

where:

σ = the standard deviation of wind speed; and

v = the mean wind speed for the recording interval

The TI is reported in one of two ways. First, as the value at 15 m/s mean speed (or more precisely, between 14.5 m/s and 15.5 m/s) only. The TI at 15 m/s provides a preliminary indication of the suitability of a turbine model for the project site. Second, as a table of values for each mean wind speed bin, *e.g.* from 1 m/s to 25 m/s. This not only supports turbine suitability, it is an input for wake models in plant design software. Usually only the TI at 15 m/s is reported in monthly or summary reports, and the TI distribution is reserved for complete reports and modelling studies. (Note that the final determination of turbine suitability is made by the manufacturer as a condition of the turbine warranty, and may take into account turbulence generated by upstream turbines.)

Wind Shear

As described in Chapter 3, 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). Alpha is derived from the averaged measured speeds and heights using the equation introduced in Chapter 4:

$$\alpha = \frac{log\left(\frac{v_2}{v_1}\right)}{log\left(\frac{h_2}{h_1}\right)} \qquad \text{Equation 13-7}$$

where v_1 and v_2 are the average speeds at the two heights h_1 and h_2.

Here are some guidelines to producing accurate estimates of shear:

- The speed ratio should 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.

- 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.

- 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.

- It is better to average the speeds before calculating the shear (rather than calculate the shear for each time record and *then* average), as it avoids undue sensitivity to extreme shear values that can sometimes occur.

- Some analysts choose to exclude speeds below 3 m/s or 4 m/s, as shear tends to be more variable in light winds, and low speeds do not contribute significantly to energy production.

Just one average shear value for each pair of heights is usually provided in wind resource reports. Charts of diurnal and seasonal shears are also sometimes produced to provide a richer understanding of the nature of the wind resource.

Wind Direction Distribution

A wind rose – a polar plot displaying the frequency of occurrence, mean wind speed, or percentage of total energy as a function of direction – is a standard element of wind resource reports. 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: $$f_i = 100\frac{N_i}{N}(\%)$$ Equation 13-8

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

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

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.

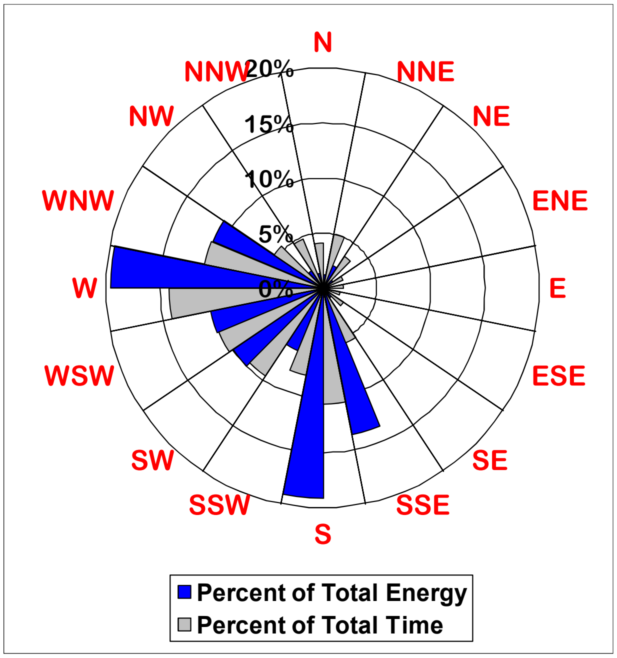


Figure 13-1. Example wind rose plot. (Source: AWS Truepower)

Figure 13-1 contains a typical wind rose plot, this one showing frequency and percent of energy. (Note the first sector by convention is centred on due north.)

Air Temperature

The average air temperature for the period of record is almost always included in resource reports. Mean temperatures by month and (less often) by time of day are often reported in table or chart form.

The delta temperature (difference between the upper and lower temperatures in a matched pair of high-accuracy sensors) is an indication of thermal stability. Though not often measured, where available, the results can be summarised in a plot showing the average temperature differential by time of day and month.

Air Pressure and Air Density

Barometric pressure can be used with air temperature to determine air density, though as noted in Chapter 5 pressure measurements are rarely taken as they are not worth the cost. Instead, the air density is estimated indirectly from the site elevation and air temperature.

If the site pressure is available, then the average air density is calculated from the ideal gas law:

$$\boldsymbol{\rho = \frac{1}{N}\sum_{i=1}^{N}\frac{P_i}{RT_i}\,(kg/m^3)} \qquad \text{Equation 13-9}$$

where i is a time record and N the total number of records in the period, and the other parameters are:

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).

Note that the sum is over *concurrently valid* records of both temperature and pressure.

If the site pressure is not available (as is usually the case), the air density is estimated as follows:

$$\rho = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{P_O}{RT_i}\right)e^{\left(\frac{-gz}{RT_i}\right)} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{353.05}{T_i}\right)e^{-0.03417\frac{z}{T_i}} \qquad \text{Equation 13-10}$$

where the last term is derived by substituting the known values of the parameters:

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)

Wind Power Density (WPD)

This common measure of the quality of the wind resource is calculated in the following way:

$$\mathrm{WPD} = \frac{1}{2N}\sum_{i=1}^{N}\rho_i v_i^3 \ (\mathrm{W/m^2}) \qquad \text{Equation 13-11}$$

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 for each record from the corresponding air temperature and elevation, as described in the preceding 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 cubic 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 always 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.

Other Metrics

Other metrics that can be reported, if available, include means solar radiation, relative humidity, and vertical wind speed. Of these, only the vertical wind speed is directly relevant to wind resource assessment, and then only in complex terrain where inclined (terrain-following) flow may occur. While vertical winds can vary over time, they are usually associated with certain directions. Thus, reporting the mean vertical wind component (as a percent or absolute magnitude) for each direction sector, similar to a wind rose, is perhaps the most useful information.

Many systems offer the ability to remotely (or directly, when on site) to monitor system health components and proper operation of the data logger or remote sensing device. One of the most common metrics is battery voltage (for both the primary computing device and any peripherals). Voltage or current measurements can be provided for heated instruments (to ensure that they are operating correctly), or for communication devices to remotely diagnose potential connection problems. Other common measurement items include communications signal strength, internal and data storage memory capacities, and indications of any extreme events that may have affected the system. The specific items and their accessibility vary by device and manufacturer, but any information on system health can provide valuable information for both preventative maintenance and data recovery applications.

13.2 REPORTS

Wind resource reports have a number of common elements. This section provides guidance on the typical report formats we see, which can be divided into Monthly or Quarterly reports (the shortest), 6-month or Annual reports (longer), and Campaign Reports (longest and most detailed). Such campaign summary reports are often be coupled with an energy production analysis in a bankable type energy production report. Feel free to depart from this guidance based on the needs of your resource measurement programme. Finally, there are some reports that serve specific needs, especially for determining turbine suitability.

Monthly or Quarterly Reports

Table 13-2 presents all of the usual parameters included in monthly and quarterly reports. The structure of such reports may follow the example included at the end of this chapter. Since the reports cover a fairly short period, they usually do not contain much tabular data, but may include some time series and other charts. They are usually no more than 2 to 4 pages long.

6-Month or Annual Reports

6-Month and Annual reports, as well as Campaign reports, typically contain the above as well as more detailed tabular data with monthly statistics, and figures displaying the results for the entire observed period of record (such as average speed by month). These reports may also include additional details on the monitoring campaign, or additional text describing the monitoring campaign and its surroundings or objectives.

Campaign Summary Reports

A campaign summary report is often completed when the monitoring campaign has ended, and is intended to summarise the entire wind resource campaign. These types of reports can include further analysis beyond the scope of this document, including estimates of the long-term wind speed potential, energy production estimates and uncertainty estimates. Detailed tables and charts summarising the meteorological data are often included, along with maps of the project area and meteorological tower locations.

Table 13-2. Sample Wind Resource Report Statistics

Report Products	Units
Data Recovery Fraction	%
Mean and Annualised 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

Turbine Suitability Assessment Reports

A summary of observed characteristics from a given monitoring site or project area can be a valuable input into the eventual turbine selection process. In particular, site-specific climatological parameters and their extremes are derived and compared with turbine classifications such as those published by the IEC. To aid in this process, the observed data is collected, validated, and compared to the standard parameter definitions for the class specific IEC design envelopes. The site extremes, or survival parameters, are of particular importance as they must be within the IEC design envelope for the turbine to be deemed suitable. The remaining parameters work in combination when loading the turbine, but are still important in the process.

Table 13-3. Sample turbine suitability report statistics

Site-Wide Parameter	Site	IEC Class IIB
50-yr, 10-min gust (m/s)	26.8	42.5
50-yr, 3 second gust (m/s)	32.5	59.5
Average Wind Speed (m/s)	6.91	8.5
Turbulence Intensity, 15m/s	0.114-0.123	14%
Maximum flow inclination angle	< 8	8 degrees
Maximum vertical wind shear (Alpha)	0.207-0.215	0.05 <= alpha <= 0.2
Annual average air density (Rho)	1.189	1.225 kg/m3
Weibull Parameters (k)	2.61-2.92	1.75<k<2.30

This process leverages much of the parameter and interval specifications outlined in previous chapters, particularly in regards to maximum, minimum, and standard deviation. Many of the parameters required are similar to those provided in monthly reports, but are intended to represent site "worst-case" conditions. Another important distinction is that these items are required to be either measured at or extrapolated to the proposed turbine hub height. An example of typical suitability parameters considered and their comparison with the IEC standard are presented in Table 13-3.

13.3 POINTS TO REMEMBER

- Descriptive parameters of the wind resource, such as those outlined in this chapter, can be useful for both summarising the recorded data and the eventual turbine selection and suitability determination process.
- Wind resource reports can and should be customised to the needs of the eventual end user.

13.4 SAMPLE MONTHLY REPORT

SITE
Summary of Wind Statistics
MONTH 2009

Site Information

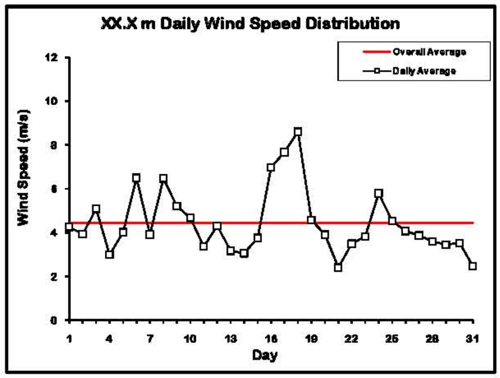
Project: Monthly Assessment of PROJECT for Wind Power Applications
Site: SITE
Location: LOCATION
UTM Site Coordinates: XXXXXX / XXXXXXX (Zone XXX)
Site Elevation: XXX m
Wind Speed Monitoring Heights: XX.X m, XX.X m
Data Averaging Interval: XX minutes
Data Sampling Interval: X seconds

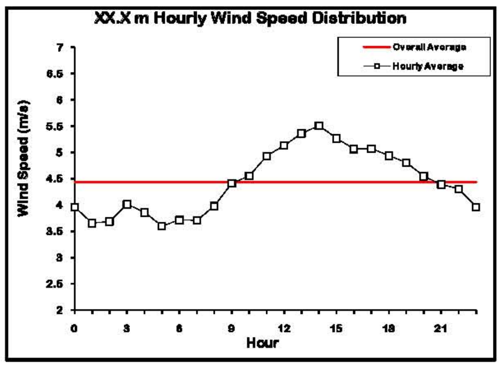
XX.X m Wind Statistics

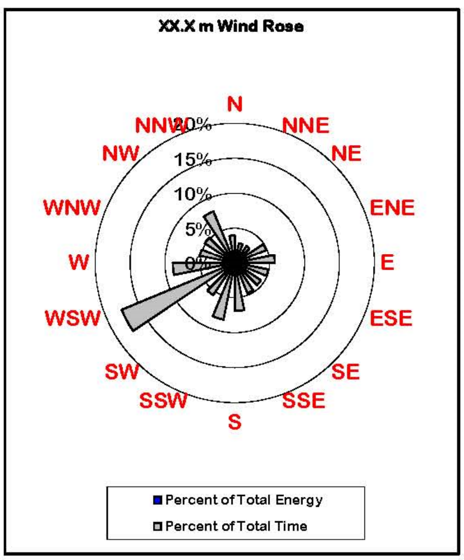
Mean Wind Speed (m/s):	4.43
Average of 10 minute Std. Dev. of Speed (m/s):	0.65
Mean XX / XX m Wind Shear:	0.XX
* Mean Turbulence Intensity:	0.13
Maximum 10 minute wind speed (m/s):	15.0
Prevailing Wind Direction:	XXX
Prevailing Energy Direction:	XXX
Mean Wind Power Density (W/m^2):	XXX
Wind Speed Data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

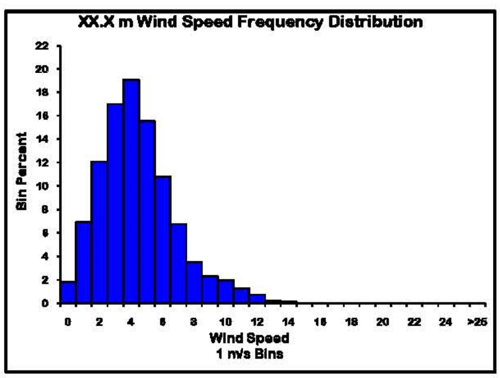
Other Measurements

**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

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