# GREBE

Generating Renewable Energy Business Enterprise

Northern Periphery and Arctic Programme

## Resource Assessment Toolkit for Wind Energy

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# The GREBE Project

## What is GREBE?

GREBE (Generating Renewable Energy Business Enterprise) is a €1.77m, 3-year (2015-2018) transnational project to support the renewable energy sector. It is co-funded by the EU's Northern Periphery & Arctic (NPA) Programme. It focuses on the challenges of peripheral and arctic regions as places for doing business, and helps develop renewable energy business opportunities in areas with extreme conditions.

The project partnership includes the eight partners from six countries, Western Development Commission (Ireland), Action Renewables (Northern Ireland), Fermanagh & Omagh District Council (Northern Ireland), Environmental Research Institute (Scotland), LUKE (Finland), Karelia University of Applied Sciences (Finland), Narvik Science Park (Norway) and Innovation Iceland (Iceland).

## Why is GREBE happening?

Renewable Energy entrepreneurs working in the NPA area face challenges including a lack of critical mass, dispersed settlements, poor accessibility, vulnerability to climate change effects and limited networking opportunities.

GREBE will equip SMEs and start-ups with the skills and confidence to overcome these challenges and use place based natural assets for RE to best sustainable effect. The renewable energy sector contributes to sustainable regional and rural development and has potential for growth.

## What does GREBE do?

GREBE supports renewable energy start-ups and SMEs:

- To grow their business, to provide local jobs, and meet energy demands of local communities.
- By supporting diversification of the technological capacity of SMEs and start-ups so that they can exploit the natural conditions of their locations.
- By providing RE tailored, expert guidance and mentoring to give SMEs and start-ups the knowledge and expertise to grow and expand their businesses.
- By providing a platform for transnational sharing of knowledge to demonstrate the full potential of the RE sector by showcasing innovations on RE technology and strengthening accessibility to expertise and business support available locally and in other NPA regions.
- To connect with other renewable energy businesses to develop new opportunities locally, regionally and transnationally through the Virtual Energy Ideas Hub.
- By conducting research on the processes operating in the sector to improve understanding of the sector's needs and make the case for public policy to support the sector.

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The Toolkit outlines best practice techniques for assessing wind resource potentials as a foundation for a wind resource assessment. The wind resource assessment entails industry-accepted guidelines for planning and conducting a wind resource measurement program to support a wind energy feasibility initiative.  These guidelines do not embody every single potential technique of conducting a quality wind measurement program, but they address the most essential elements based on field-proven experience.

The scope of the Toolkit covers:

- Wind resource assessment 101
- Sitting of monitoring systems
- Measurement parameters and monitoring instruments
- Installation of monitoring stations
- Site operation and maintenance
- Data collection and management
- Data validation
- Data processing
- Comparison of observed wind data with historical norm
- Wind flow modelling

# Wind resource assessment 101

## Current status of global wind power

The first wind turbines for electricity generation were developed at the beginning of the 20th century. Thus, wind technology is one of the most mature and proven technologies on the market. In 2015, the wind energy industry installed 12.8 GW in the EU – more than gas and coal combined. Globally, the current wind power installation capacity has reached 435 GW with a significant growth rate of 16.4% in 2014 and 17.2% in 2015. Wind turbines offer the prospects of cost efficient generation of electricity and fast return on investment. The economic feasibility of wind turbines depends primarily on the wind speed. Usually, the greater the long term annual average wind speed, the more electricity will be generated and the faster the investment will pay back. However, it is important to access the wind power potential (WPP) at any prospective location to decide the capacity of wind resource for electricity generation within available time limits of wind duration. Hence, it is relevant to observe the wind characteristics and type of wind turbine technology suitable for any given promising location. These factors are very much helpful for wind power developers and investors to make a decision with respect to the economic constraints.

The total global WPP of about 94.5 TW was estimated from the countries like USA, European Union (EU), Russia, and others. The WPP input from the rest of the countries is little in contrast with USA, EU, and Russia. The total energy consumption of about 103,711 TWh was assessed all over the world for numerous sectors such as industries, cooling and heating, and transport, out of which 19,299 TWh is used up by the power sector as per the official evaluations of IEA for 2011. Thus, the total worldwide potential is adequate to cover the entire world's energy demand by supposing roughly an average of about 2000 full load hours. As per the official estimates, the global wind power installed capacity has reached 435GW out of the global estimated potential of 95TW. [1]

## Objectives and approaches

A wind resource assessment necessitates organisation and harmonization while at the same time it is limited by budget constraints and schedule restrictions. The assessment necessities a clear set of objectives in order to identify the best approach and achieve the desired results. The success of a wind resource assessment is contingent on the quality of the program’s assembled assets — sound siting and measurement techniques, trained staff,

[1] A comprehensive review of wind resource assessment, K.S.R. Murthy, O.P. Rahi, 2017.

quality equipment, and comprehensive data analysis methods. Numerous methodologies have been defined to assess a wind resource within a given land area. The favoured methodology will rely on the objectives and on preceding experience with wind resource assessment in the region and in similar terrain. These approaches can be categorized as three main stages of wind resource assessment: site identification, preliminary resource assessment and micrositing.

**Preliminary site identification** - This process monitors a comparatively large region for apt wind resource areas grounded on data collected through airport wind data, topography, flagged trees, wind maps and other publicly available data. It also takes into consideration positive and adverse aspects, such as constructability, access, and environmental deliberations. The first step in defining area's potential, is to collect all the relevant geographic data in a Geographic Information System (GIS). This assists efficient work and precise choices during the site-selection procedure. The most valuable geographic data can be attained through the use of the following in the GIS:

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

At the end of the toolkit you can find information on useful tips/websites/places where you can obtain this information from. Once a GIS project has been generated, suitable benchmarks can be applied to choose candidate sites. When contestant sites have been designated, much of the monitoring design can be determined in a virtual environment. A GIS is particularly useful for determining the most effective locations to install monitoring towers.

**Preliminary resource assessment**[2] – once possible sites are identified, the second step in the assessment is the preliminary identification and classification of the wind resource. This would assist the positioning of the first wind monitoring towers. The aims of this stage of the resource assessment are:

- Conclude or confirm whether adequate wind resources are present within the area to validate further site-specific surveys.
- Compare areas to tell between comparative development potential.
- Acquire demonstrative data for appraising the performance and/or the economic viability of selected wind turbines.
- Screen for potential wind turbine installation sites.

**Wind monitoring campaign**[3] - achieve the best possible understanding of the wind resource at the turbine hub height and through the rotor plane across the project area. This objective can be realised through a selection of monitoring options, including tower distribution, height, instrumentation and ground-based remote sensing. Once the measurement phase is substantially completed it is followed by data analysis and modelling.

- Tower distribution - location and dispersal of meteorological towers within a project area to diminish the uncertainty of the wind resource at potential turbine locations. Central attentions that should be considered are, but not limited to:
  - Resemblance/representativeness of the chosen area to the larger project area.
  - Capacity to capture the variety of settings experienced by future turbines.
  - Distance to future turbines, if the turbine layout is known.
  - Multiple masts, if needed.
- Tower height - 60metre meteorological towers are the mainstream height of most wind monitoring programs. Taller towers as well as remote sensing systems may be employed, measuring the wind resource at the hub height (and above) of the proposed wind turbines. The direct measurement at hub height, rather than extrapolation from lower measurement heights, diminishes doubts in the wind resource.
- Tower Instrumentation - the collection of wind speed data, wind direction, and air temperature data are the most imperative indicator of a site's wind energy resource. Various measurement heights are crucial to conclude on a site's wind shear characteristics. Wind direction frequency information is important for optimizing the layout of wind turbines within a wind farm. Air temperature measurements help to

[2] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.
[3] Wind Resource Assessment Handbook, NUSERDA, 2010.

provide additional information about the site conditions and to determine air density.

- Ground-Based Remote Sensing. Sodar (sonic detection and ranging) and lidar (light detection and ranging), two recent opportunities for measuring wind speed. They can be advantageous for spot-checking the wind resource at different points within the project area and for measuring the wind shear throughout the rotor plane. Short-term (4-6 week) campaigns are typical, but longer or multiple campaigns may be desirable for large projects (greater than 100 MW), in complex terrain, or for projects where significant seasonal variation of shear is expected.
- Measurement Plan – purpose is to guarantee that all facets of the wind monitoring program are pooled to deliver comprehensive data required to meet the wind energy program objectives. It should be documented in writing, and revised and agreed by the project participants before it is executed. The recommended minimum duration of the wind monitoring is one year, but a longer period produces more reliable results. The data recovery for all measured parameters should be as high as possible, with an objective for most tower sensors of at least 90%, with few or no lengthy data gaps. The rate realised will be influenced by a number of factors, including the remoteness, weather conditions, the type of instruments, and methods of data collection.

  The plan should stipulate the following elements:
  - Measurement parameters (e.g., speed, direction, temperature)
  - Equipment nature, quality, and budget
  - Equipment monitoring heights and orientations
  - Number and location of monitoring masts
  - Minimum preferred measurement precision, length, and data recovery
  - Data sampling and recording intervals
  - Parties responsible for equipment fitting, upkeep, data validation, and reporting
  - Data transmission, screening, and processing techniques
  - Quality control measures
  - Data reporting intervals and format.
- Monitoring Strategy – necessitates good management, qualified staff, and adequate resources. All parties involved have to be aware of their responsibilities, lines of authority, accountability, objectives of measurement plan and schedule. High standards of data accuracy and completeness call for suitable levels of staffing with the right qualifications, an investment in quality equipment and tools, prompt responsiveness to ad hoc events, access to spare parts, routine site visits, and timely review of the data.
  - Station operation and maintenance - continuing maintenance and vigilant documentation of the wind resource monitoring station is essential to

preserve the reliability of the measurement campaign and to accomplish the objectives of the measurement plan.

- Data collection and handling – the process has to guarantee that the data is accessible for analysis and secure from corruption or loss.

- Quality assurance plan[4] – a systematized and comprehensive action agenda for assuring the successful collection of high-quality data. The program manager should inaugurate and validate the quality assurance plan, thus giving it authority for all personnel. A Quality Assurance Coordinator is linked between the plan and the program management, who is an expert on the routine requirements for collecting valid data. It is suggested that the quality assurance plan includes the following constituents:
    - Equipment procurement tied to the program's specifications
    - Equipment calibration technique, rate of recurrence, and reporting
    - Monitoring station installation, verification, and operation and maintenance checklists
    - Data collection, screening, and archiving
    - Data analysis guidelines (including calculations)
    - Data validation methods, flagging criteria, reporting frequency, and format
    - Internal audits to document the performance of those responsible for site installation and operation and maintenance, and for data collection and handling.

**Micrositing** - core aim is to quantify the small-scale variability of the wind resource over the terrain of interest and to position one or more wind turbines on a parcel of land to maximize the overall energy output of the wind plant. At this stage, the wind resource is characterized as accurately as possible at all relevant temporal and spatial scales. Step in micrositing are:

- Data validation - Once the data from the monitoring system have been successfully obtained and transferred to an office computing environment, the data can then be validated. During this process, the extensiveness and reasonableness of the data are evaluated and validated, and suspect values are highlighted within the data records.
- Characterizing the observed wind resource – after wind resource is validated, the data can be used to produce reports specific to the site wind resource statistics to assist in characterizing the resource.
- Estimating the hub-height resource - assessing a wind turbine's energy production potential often entails extrapolating the measured data from the top height of a tower to the intended turbine hub height. The task involves a cautious and often

[4] Wind Resource Assessment Handbook, NUSERDA, 2010.

subjective scrutiny of data about the site, including the local meteorology, topography, and land cover, as well as the measured wind shear.

- The climate-adjustment process - correcting the observed wind measurements to the site's historical norm, in order to understand how the measurements compare, as wind speeds can vary substantially from the norm, making the measurement from a short-term wind resource assessment campaign potentially misrepresentative. A process known as "measure, correlate, predict" (MCP) is used to relate onsite measurements to a long-term reference, thereby reducing the uncertainty of associated energy estimates.
- Wind flow modelling - onsite measurements are restricted to a few locations within the project area, wind flow modelling can estimate wind resource at all locations.

# Sitting of monitoring sites

The chief goal of a siting program is to choose nominee wind project sites and locations for wind monitoring systems. As the preliminary exploratory region can be quite large, the siting method should be designed so it can efficiently focus on the most suitable areas. There are three core stages in the siting process:

- Identification of potential wind development sites
- Grading and assessment of nominee sites
- Selection of tower and other monitoring location(s) within the nominee sites

## Use of wind resource data sources

Wind resource public data sources can be valuable in the early stage of the siting process. Those data sources would not be sufficient to define project viability but they can be the starting point for exploration of wind developments and potential sites. Regrettably, most historical wind data was not collected for wind energy assessment purposes, so the results characterized the mean conditions near population centres in relatively flat terrain or low elevation areas.

**Wind resource maps**[5]

Regional wind resource maps are a useful starting point for identifying potentially attractive wind resource areas. They have the extra benefit of being compatible with GIS. Reasonably precise and thorough wind resource maps have been created using mesoscale weather

[5] Wind Resource Assessment Handbook, NUSERDA, 2010.

models, microscale wind flow models, and high-resolution elevation and land cover data, with spatial resolution of regional maps ranges from 200m to 5km. With increasing numbers of ground-based measurements from specially installed anemometer stations, as well as operating data from commissioned wind farms, the accuracy of wind resource maps in many countries has improved over time. In addition to the publicly available sources listed at the last section of the toolkit, maps are available as commercial products through specialist consultancies, or users of GIS software can make their own using publicly available GIS data. Although the accuracy has improved, it is doubtful that wind resource maps, whether public or commercial, will remove the prerequisite for on-site measurements for utility-scale wind generation projects.

Resource maps can help accelerate the process of site identification, and the existence of high quality, ground-based data can shorten the amount of time where on-site measurements need to be collected. Care must be taken when using wind resource maps, as most maps present estimates of the long-term mean wind speed at a particular height above ground, which cannot be translated directly into production by a wind turbine, which depends on other factors such as the speed frequency distribution, air density, and turbulence, as well as specific turbine model and hub height. Some wind map vendors offer such complementary data upon request, together with appraisals of capacity factor for particular turbine models.

**Site specific wind data**

Publicly available wind data can be useful for evaluating the wind resource in a region, particularly if the wind monitoring stations are in locations that are representative of sites of interest for wind projects. An example would be a tall tower on a ridge line, but also airport and other weather stations. Several essentials should be reflected when considering using data from site specific instruments:

- 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
- Period of data record
- Quality-control and analysis applied to the data

Wind data tends to be more characteristic of the nearby area where the terrain is comparatively flat, since at a complex terrain, the capability to reliably extrapolate data beyond a station’s immediate vicinity is more restricted and might call for expert judgment and wind flow modelling. Even in flat terrain, good exposure to the wind is crucial, specifically for short towers. Data from existing meteorological towers is unlikely to be able to substitute onsite measurements from a wind monitoring campaign but can be used in a preliminary assessment.

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

$$v_2 = v_1 \left(\frac{h_2}{h_1}\right)^{\alpha}$$

Where:

$v_2$ = the unknown speed at height $h_2$

$v_1$ = the known wind speed at the measurement height $h_1$

$\alpha$ = the wind shear exponent

The ambiguity in the estimated speed depends on both the ratio of heights that have to be extrapolated and the doubt in the wind shear exponent. If the upper height is a large multiple of the lower height, the uncertainty may be quite large, and extrapolating from 10m to 80m may bring about an uncertainty of 10%-30% in the resultant speed. Wind shear exponents fluctuate extensively subject to vegetation cover, terrain, and general climate.

| Terrain Description | Power law exponent, α |
|---|---|
| Smooth, hard ground, lake or ocean | 0.10 |
| Short grass on untilled ground | 0.14 |
| Level country with foot-high grass, occasional tree | 0.16 |
| Tall row crops, hedges, a few trees | 0.20 |
| Many trees and occasional buildings | 0.22 – 0.24 |
| Wooded country – small towns and suburbs | 0.28 – 0.30 |
| Urban areas with tall buildings | 0.4 |

Table 1 Estimation of the wind shear exponent according to the terrain [6]

The table above gives an estimation of the wind shear exponent according to the terrain.

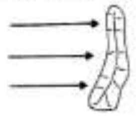
**Topographic indicators**

The topographic screening should attempt to identify features that are likely to experience a greater mean wind speed than the general surroundings. This process is especially

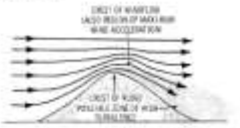
[6] https://www.geocaching.com/geocache/GC1BF99_twin-groves-a-lesson-in-wind

important for areas containing little or no relevant historical wind speed data. Features that are likely to be windier include:

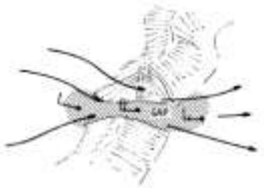
- Ridges oriented perpendicular to the prevailing wind direction



- Highest elevations within a given area



- Locations where local winds can funnel.




[7]

The terrains that are considered most appropriate for potential wind energy sites are elevated ridges that are perpendicular (90 degrees) to the prevailing winds. Elevated terrain causes accelerating forces that increase local wind speeds. The ridges intercept the winds and then compress and accelerate air as it moves upwards, increasing the wind speed at the ridge top. Therefore exposed ridges are known to be sources of higher localized winds. Other areas where the wind accelerates are steep divides or valleys that funnel the wind. For the purpose of wind power meteorology, which is primarily concerned with the wind flow from 10 to 200m above the ground, the effects of the topography can be divided into three typical categories:[8]

- **Roughness:** The collective effect of the terrain surface and its roughness elements, leading to an overall retardation of the wind near the ground, is referred to as the roughness of the terrain. The more prominent the roughness of the earth's surface, the more the wind will be slowed down. In the wind industry, people usually refer to roughness classes or roughness lengths, when they evaluate wind conditions in a landscape. A high roughness class of 3 to 4 refers to landscapes with many trees and buildings, while a sea surface is in roughness class 0. Concrete runways in airports are in roughness class 0.5. The same applies to flat, open landscape.
- **Obstacle**: Close to an object, such as a building or shelterbelt, the wind is strongly influenced by the presence of the obstacle, which may reduce the wind speed considerably. Obstacles will decrease the wind speed downstream from the obstacle.

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[7] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.
[8] http://www.windpower.org/en

The decrease in wind speed depends on the porosity (open area divided by the total area of the object facing the wind) of the obstacle, i.e. how "open" the obstacle is. A building is obviously solid, and has no porosity, whereas a fairly open tree in winter (with no leaves) may let more than half of the wind through. In summer, however, the foliage may be very dense, so as to make the porosity less than, say one third. The slowdown effect on the wind from an obstacle increases with the height and length of the obstacle. The effect is obviously more pronounced close to the obstacle, and close to the ground.

- **Orography**: The term orography refers to the description of the height variations of the terrain, referenced to a common datum such as the mean sea level. When the typical scale of the terrain features becomes much larger than the height of the points of interest they act as orographic elements to the wind. Near the summit or the crest of hills, cliffs, ridges and escarpments, the wind accelerates, while near the foot and valley it will decelerate.

Topographic maps also provide an initial look at other site characteristics, including:

- Available land area
- Positions of existing roads and dwellings
- Land cover (e.g. forests)
- Political boundaries
- Parks
- Proximity to transmission lines

Following the topographic screening, a preliminary ranking can be assigned to the list of candidate sites based on their estimated wind resource and overall development potential.

Tree flagging – a preliminary assessment following the topography, can be made using the technique known as wind deformed conifer trees. The deformation ratio reflects the amount of crown asymmetry and trunk deflection caused by wind.

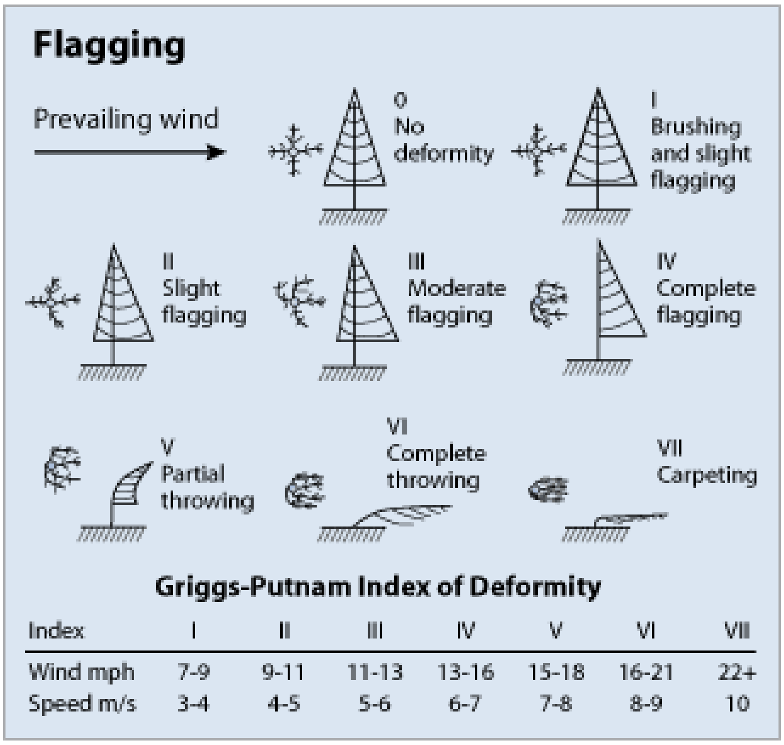



Figure 2 Griggs-Putnam Index of Deformity [9]

Trees represent an inexpensive, simple, and quick method to identify the favourable locations for availability of wind power.

**Field surveys**

Visits should be made to all apt areas with the goal of confirming site settings. Matters of significance comprise of:[10]

- Available land area
- Land use
- Location of obstructions
- Trees deformed by persistent strong winds (flagged trees)
- Accessibility to the site
- Potential impact on local aesthetics
- Cellular phone service reliability for data transfers
- Possible wind monitoring locations.

It is a good idea to keep a ranking matrix while making the visit, where scores are assigned to each criterion and weighted accordingly to their importance. The final scores are summed at the end to reach a composite ranking. While doing the surveys it is important to have a detailed topographic map and GPS system in order to record the exact location

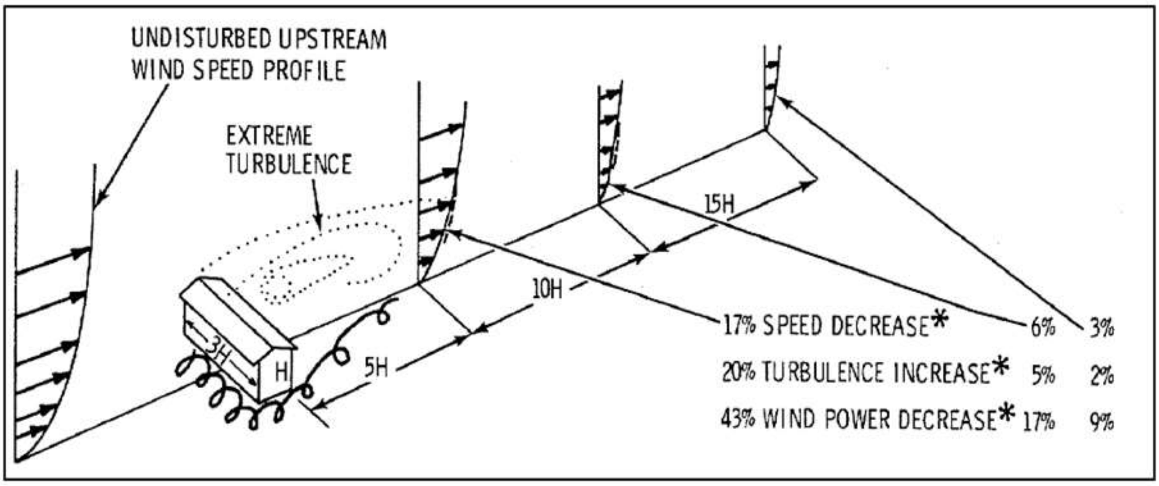
[9] http://www.daviddarling.info/encyclopedia/S/AE_small_wind_electric_system_resource_evaluation.html
[10] Ibid 7

(latitude, longitude, and elevation) of each point of interest and link simultaneously to a laptop running a GIS. When evaluating an anticipated tower location, the assessor can also evaluate the soil conditions so the proper anchor type can be chosen later. In forested settings, it should be determined whether tree clearing will be required for tower installation.

Field visits also offer an occasion to become familiar with landowners who may be affected by the proposed wind project. The monitoring program's objectives can be presented in a friendly, face-to-face conversation, and the landowner's questions and concerns should be noted and addressed, if possible. If the project is of a larger scale and a community might be affected by the proposal, it is good before going forward to conduct a community consultation and make sure that all the questions/problems/issues are addressed. It is in the project's best interests to explore this theme thoroughly during the initial site evaluation. Meticulous visual reproductions can be produced to model how a suggested project will look from a range of positions and in different light conditions. This type of exploration can assist the community understanding of a project's possible impact and aid developers to recognise where a mitigation plan might be necessary. [11]

**Tower placement**

Several essential recommendations should be followed when selecting the locations for new, dedicated monitoring towers. The placement of a mast is crucial for the precision of the wind flow modelling. Place the towers as far away as possible from substantial impediments that would not be characteristic of obstructions at likely turbine location. Siting a tower near obstructions such as trees or buildings can adversely affect the analysis of the site's wind characteristics.  The  figure below exemplifies the effects of an undisturbed airflow that encounters an obstruction.




[11] Wind Resource Assessment Handbook, NUSERDA, 2010.

Figure 3 [12]

The presence of these obstructions can modify the apparent magnitude of the site's overall wind resource, wind shear, and turbulence levels. As a rule, if sensors must be near an obstruction, they should be situated at a horizontal distance no closer than 10 times the height of the obstruction in the prevailing wind direction. The bottom-most speed sensors on the tower should be placed well above the tree canopy, if possible, to ensure an accurate measurement of wind shear.

- For small projects, select a location that is representative of where wind turbines are likely to be sited – not necessarily where the best wind is to be found.
- For large projects, select a diverse set of locations representing the full range of conditions where wind turbines are likely to be sited.

One approach to tower appointment is to keep the distance between any future turbine and the nearest tower within definite limits. With this method, it is necessary to envision a specific turbine layout before siting the towers. This may help determine the appropriate number of towers and reduce the wind flow modelling uncertainty. Distance is not the only norm that should be taken into account. It is likewise imperative that the mast locations be characteristic of the terrain in which the turbines will ultimately be mounted. While there is no clear industry standard, the following guidelines may be followed:

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

[13]

[12] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.

When placing a mast tower that is higher than the 60m, some challenges need to be taken into account:

- There is a need for a larger clear area to mount a higher tower. Thus, the height of the mast might be limited by the surroundings (environmental considerations), if it is to be based, in a woody area.
- The higher the tower, the more power is required. In remote, peripheral locations, this might call for a custom-designed power system, which would put up the price for the resource assessment.
- When the mast is taller the challenges associated with severe weather are bigger – icing, high winds, lightning, etc., that might call for additional maintenance which again raises the costs.

**Land leasing**

It is key to inquire whether permits are required before a tower is mounted. Tilt-up towers typically fall into the category of temporary structures, so permitting requirements are generally minimal. An apt choice is an option agreement (anytime between 3-5 years), which allows the developer to assess the wind resource and gives the right to exercise the option and lease the land or not. This decision protects both the developer, by assuring the developer the land will be available if the project goes forward, and the landowner to go forward with the use of his land if the project does not go further.

Formal lease agreements should be negotiated between the developer and the landowner to protect both parties, such as: [14][15]

- The tower location - The lease should clearly state where the meteorological towers can be positioned and the total area they will occupy. Any anticipated impediments from residences and property lines should be stated.
- Access to premises - The developer needs to have the right to access the land and use 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.
- Duration of monitoring period – should be clearly stated.
- Payment schedule - The agreement should also outline how the landowner will be compensated and the payment schedule. During the option period, the developer typically pays a fee to the landowner for the right to place wind monitoring equipment on the site and sometimes to compensate for lost income

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[13] Wind Resource Assessment Handbook, NUSERDA, 2010.
[14] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.
[15] Wind Resource Assessment Handbook, NUSERDA, 2010.

and construction-related disruptions. The compensation can fluctuate 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.

- Approved Uses: The lease should stipulate what uses the landowner reserves for the land around the monitoring equipment. For instance, the landowner may reserve the right to continue to grow crops or raise cattle.
- Crop Protection: Typical lease provisions require developers to use their best efforts to minimize damage, and to compensate landowners for any damage that may occur. Mitigation measures to be covered in the lease agreement may include soil preservation or DE compaction to remedy the impacts of project-related vehicle traffic.
- Liability & Insurance - The agreement should contain provisions to protect landowners from any liability arising from accidents. The agreement should also require that the developer carry a general liability insurance policy.

All of the above mentioned requirements will be different according to the national legislations, frameworks, environmental legislation, etc., so further enquiries are necessary.

# Measurement Parameters and Monitoring Instruments

In order to proceed to the monitoring station instrumentation required to collect the data, it is important to introduce the basic wind parameters. Meteorological instruments (sensors, probes, or monitors) are designed to monitor specific environmental parameters. This section of the toolkit gives the basic information for the parameters for measuring wind speed, wind direction, and air temperature and the corresponding instruments to do it.

## Wind Speed and Monitoring Instruments

Wind speed refers to the average speed over a given period, while wind gusts are a rapid increase in strength of the wind relative to the wind speed at the time. Wind speed is affected by a number of factors and conditions, operating on varying scales (from micro to macro scales). These comprise of the pressure gradient, Rossby waves and jet streams, and local weather conditions. There are also links to be found between wind speed and wind direction, notably with the pressure gradient and terrain conditions. Pressure gradient is a term to describe the difference in air pressure between two points in the atmosphere or on the surface of the Earth. It is vital to wind speed, because the greater the difference in pressure, the faster the wind flows (from the high to low pressure) to balance out the variation. The pressure gradient, when combined with the Coriolis Effect and friction, also influences wind direction. Rossby waves are strong winds in the upper troposphere. These operate on a global scale and move from West to East (hence being known as Westerlies). The Rossby waves are themselves a different wind speed from what we experience in the lower troposphere.

Multiple measurement heights are encouraged for determining a site's wind shear characteristics, conducting turbine performance simulations at several turbine hub heights, and for backup. Typical heights are 40m, 25m, and 10m.[16]

- 40m: approximate hub height of most utility-scale wind turbines. Actual hub heights are usually in the 50m to 65m range.
- 25m: the minimum height reached by the blade tip portion of a rotating turbine rotor and will help define the wind regime encountered by a typical turbine rotor over its swept area.
- 10m: This is the universally standard meteorological measurement height. However, in locations where the interference of local vegetation at this height is unavoidable, an alternative low-level height of 10m above the forest canopy may be used.

For speed of wind measurement the basic sensors used for measuring wind speed are anemometers. Multiple anemometers and measurement heights are strongly encouraged to maximize data recovery and to accurately determine a site's wind shear. There are 3 anemometer types used for the measurement of horizontal wind speed.

- **Cup anemometer** – the most popular because of its low cost and generally good accuracy, where a vertical shaft supports a cup assembly, used for rotation (see the figure below). A cup faces the wind always, involving typical technique to develop an aerodynamic structure which converts the wind pressure into rotational torque. The cup rotates in proportion with the incoming wind speed over the specified range. The most commonly used anemometer is a rotating cup anemometer. The signal generated by the rotating cups varies in proportion with the wind speed. The signal takes mechanical or electrical forms, and can be continuous or discrete. Continuous signals can be used to find instantaneous wind speeds whereas discrete are used to find mean of wind speed over a specific period of time.[17] This type of anemometer has a number of advantages: it does not require a power supply, its structure is simple, and it remains relatively problem-free.

[16] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.

[17] Intelligent Schemes for Wind Data Analysis, CHAPTER IV Wind Data Measurement and Analysis, Jain University, 2016.

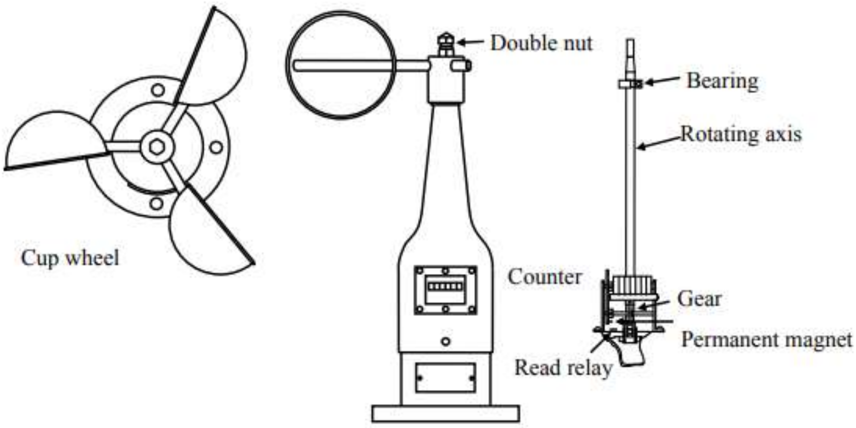


Figure 4 How a cup anemometer works. [18]

- **Propeller Anemometer** - A propeller anemometer has a sensor with a streamlined body and a vertical tail to detect wind direction and a sensor in the form of a propeller to measure wind speed integrated into a single structure. It measures wind direction and wind speed, and can indicate/record the instantaneous wind direction and wind speed in remote locations. It also measures the average wind speed using wind-passage contacts or by calculating the number of optical pulses. Like a cup anemometer, a propeller anemometer generates an electrical signal whose frequency (or magnitude) is proportional to the wind speed. This type of anemometer can record slightly lower speeds than cup anemometers under turbulent conditions.[19]

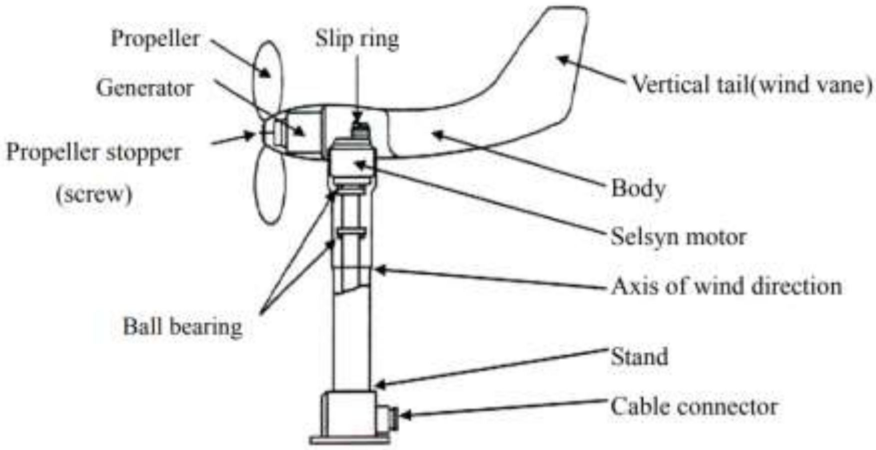


Figure 5 How a propeller anemometer works.[20]

[18] https://www.explainthatstuff.com/anemometers.html
[19] Wind Resource Assessment Handbook, NUSERDA, 2010.

- **Sonic anemometer** - Sonic anemometers operate by measuring the time taken for a pulse of sound to travel between a pair of transducers. The geometry can be set up to measure wind in two or three dimensions. Because it has no rotational inertia, it is more responsive to rapid speed and direction fluctuations than cup or propeller anemometers. Sonic anemometers provide fast and accurate measurements of three dimensional wind speed. Sonic anemometers are able to operate in most conditions experienced in the atmosphere, however heavy rain affects data quality from some models as water droplets on the transducers significantly affect pulse times and if ice builds up on the transducers measurements are similarly affected.

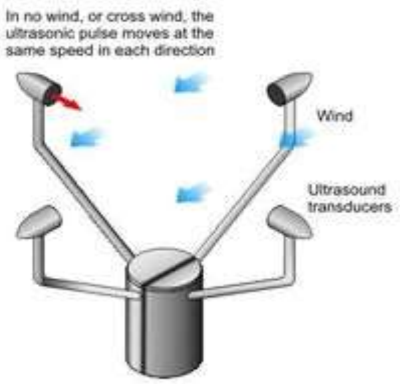


Figure 5 How sonic anemometer works.

For the right choice of anemometer you have to reflect on the following:[21][22]

- **Anticipated application** - Not every anemometer is appropriate to every setting. Environments that may cause teething troubles include icing, heavy rain, lightning, sand and dust, extreme temperatures, and salt-water intrusion. The most common issue in the NPA is icing, which can cause anemometers and direction vanes to read incorrectly or stop working altogether. Heated anemometers are available from most manufacturers, and it is recommended that at least one or two be installed on every mast where significant icing is expected to minimize data loss.
- **Starting Threshold** - this is the minimum wind speed at which the anemometer starts and sustains rotation. For wind resource assessment purposes, it is more important for the anemometer to survive a 25m/s wind gust than to be reactive to winds under 1m/s. Thus, choice of anemometer is important.
- **Distance Constant** -This is the distance the air travels past the anemometer during the time it takes the cups or propeller to reach 63% of the equilibrium speed after a

[21] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.
[22] Wind Resource Assessment Handbook, NUSERDA, 2010.

step change in wind speed. This is the "response time" of the anemometer to a change in wind speed. Longer distance constants are usually associated with heavier anemometers; inertia causes them to take longer to slow down when the wind decreases. Anemometers with larger distance constants may overestimate the wind speed. This is because they tend to respond more quickly to a rise than to a drop in speed. Sonic anemometers are not susceptible to this "over-speeding" effect. Anemometers commonly used for resource assessment have distance constants ranging from 1.8m to 3.0m.

- **Reliability and Maintenance** - A wind resource monitoring operation usually consists of collecting wind data for one or two years. To evade the requirement for repeated and expensive substitutes, the use of anemometers adept for surviving and holding their calibration in the field for the period required is recommended. In some environments, a mixture of sensor types (sonic, propeller, cup anemometer) is required to attain a balance between survivability, data recovery, and accuracy.
- **Redundant anemometers** - The use of redundant anemometers at a given height is suggested for decreasing the risk of wind speed data loss due to a failed primary sensor. Redundant sensors are positioned to not obstruct with the wind and the primary sensor measures. At the beginning of the measurement program, the measurements from the redundant sensor should be compared with the primary sensor in a side-by-side field comparison of sequential recorded values. This test will define the variance in readings attributed to the instruments themselves. To guarantee that the collected sample size is adequate and demonstrative of a broad range of wind speeds, the test period should last at least one week. Generally, it will be less expensive to provide sensor redundancy than to conduct an unscheduled site visit to replace or repair a failed sensor.
- **Sensor Calibration**: The transfer function (slope and offset) for cup and propeller anemometers can be either a default (or consensus) function previously established by testing a large number of sensors of the same model, or it can be one measured specifically for the sensor that was purchased. In the latter case, the sensor is said to be calibrated. A benefit of using calibrated is that there is a bigger guarantee that unapt sensors will be discovered before they are installed in the field. 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.
- **Response to Off-Horizontal Wind**: In fairly steep terrain, the wind often has a substantial vertical element. Turbine power curves use horizontal speed, the vertical element needs to be removed from the measurement. The 3D sonic anemometers, measure the horizontal and vertical wind components independently. Propeller anemometers are sensitive only to the horizontal component, just like wind turbines. Some cup anemometers (3D anemometers) are sensitive to the vertical element and thus can produce a deceptive evaluation of the horizontal speed. Adjustments can

be made for these anemometers if the vertical wind speed can be measured and the anemometer's sensitivity to the inclination angle is known.

## Wind Direction and monitoring instruments

To define the predominant wind direction(s), wind vanes should be fitted at all important monitoring levels. Wind direction frequency data is central for identifying favoured terrain shapes and orientations, and for optimizing the layout of wind turbines within a wind farm. Wind direction is usually reported in cardinal directions or in azimuth degrees. Wind direction is measured in degrees clockwise from due north and so a wind coming from the north has a wind direction of 0 degrees; one from the east is 90 degrees; one from the south has a wind direction of 180 degrees. One from the west is 270 degrees or -90 degrees. In general, wind directions are sometimes expressed as -180 to 180, and sometimes 0 to 360.

A wind vane is used to measure wind direction. Vanes are classified into wind vane and aero vane types. Wind vanes are used alone, while aero vanes are used with a propeller anemometer and a wind direction plate, which looks like the vertical tail part of an airplane.

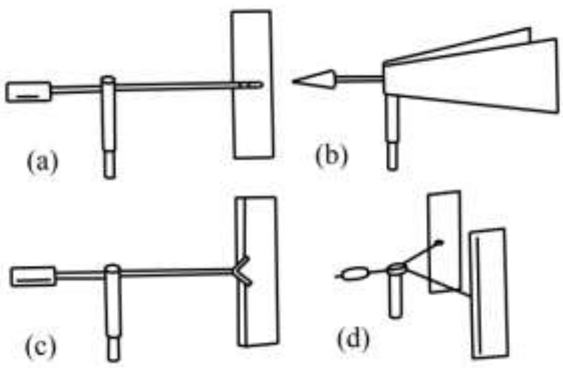


Figure 6 Different types of wind vanes.

The figure above show the different types of wind vanes. A wind direction transmitter is a device used to convert the angle of the wind direction axis into an electrical signal. Equipment including a potentiometer, a selsyn motor and an encoder system is used for this purpose. This electrical signal is conveyed via wire to a data logger and transmits the vane's position to a known reference point.The data logger delivers a known voltage across the entire potentiometer component and measures the voltage where the wiper arm contacts a conductive element. The ratio between these two voltages governs the position of the wind vane. This signal is interpreted by the data logger system, which uses the ratio (a known multiplier) and the offset (a known correction for any misalignment to the standard reference point) to calculate the actual wind direction.  Electrically the linear potentiometer element does not cover a full 360°. This "open" area is the deadband of the wind vane.

When the wiper arm is in this area, the output signal is random. Therefore, the deadband area should not be aligned into or near the prevailing wind direction.[23]

When selecting a wind vane, you ought to use the similar selection criteria as for the anemometer. Specific consideration has to be paid to the size of the open deadband area of the potentiometer; this should not exceed 8°. The resolution of the wind vane is also important. Some divide a complete 360° rotation into 16 x 22.5° segments. This resolution is too coarse for optimizing the layout of a wind turbine array.

To define the wind direction with sufficient redundancy, it is suggested that wind vanes be mounted on at least two monitoring levels. Ideally, they should not be fixed on the same booms or even at the same heights as the anemometers as they could impede attaining correct speed readings. It is usual to fit the direction vanes one or two meters below the anemometers.[24]

## Air temperature and monitoring instruments

Air temperature is a significant factor of a wind farm's operating environment. Usually measured either near ground level (2 to 3m), or near hub height. In most locations the average near ground level air temperature will be within 1°C of the average at hub height. It is also used to calculate air density, a variable prerequisite to estimate the wind power density and a wind turbine's power output.

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

## Data loggers

All data loggers store data locally, and many can transfer the data to another location through cellular telephone, radiofrequency telemetry, or satellite link. Remote data transfer allows the user to acquire and inspect data without making regular site visits and to confirm that the logger is operating properly. The data logger must be well-suited with the chosen

[23] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.
[23] Wind Resource Assessment Handbook, NUSERDA, 2010.

sensor types and be able to support the preferred number of sensors, measurement parameters, and sampling and recording intervals. It is prudent to mount the logger in a noncorrosive, water-tight, lockable enclosure to protect it. It is recommended that the data loggers are adept to store data values in a consecutive format with corresponding time and to have an on-board real-time clock so that the time stamps will remain accurate even if the logger loses power. Also it is crucial to have internal data storage capacity of at least 40 days, to have non-volatile memory storage so that data is not lost if power fails and to offer remote data collection options. It is preferable for data loggers to be able to operate in anticipated environmental extremes and operate on battery power (which may be augmented by other sources such as a solar panel).

Data loggers can be grouped by their method of data transfer, either in-field or remotely.

- **Manual Data Transfer** - This method call for site visits to transfer data:
    - Step 1 - Remove and replace the current storage device or transfer data directly to a laptop computer
    - Step 2 - upload the data to a central computer in an office.

The advantage of the manual method is that it encourages a visual on-site inspection of the equipment. Disadvantages include additional data handling steps (thus increasing potential data loss) and frequent site visits.

- **Remote Data Transfer** - requires a telecommunications link between the data logger and the central computer. The communications system may incorporate direct-wire cabling, modems, phone lines, cellular phone equipment, radio frequency (RF), telemetry equipment, satellite-based telemetry, or for redundancy, a combination of these components.  A benefit from this method is that you can recover and examine data more frequently, which allows for prompt identification of site problems. Disadvantages include the cost and time required to purchase and install the equipment. Also some sites have poor cellular coverage, and other telecommunications options can be expensive.  Data loggers with remote data transfer via cellular communications are gaining attractiveness because of their simplicity of use and sensible 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 phone. Where the signal strength is weak, an antenna with higher gain can sometimes be successful. There are two basic remote data retrieval types. [25][26]

[25] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.

[26] Wind Resource Assessment Handbook, NUSERDA, 2010.

- Call out - require the user to initiate the communications at prescribed intervals. This method necessitates the user to oversee the telecommunication operation. Steps include initiating the call to the in-field data logger, downloading the data, verifying data transfer, and erasing the logger memory. Some call-out data logger models are compatible with computer-based terminal emulation software packages with batch calling. Batch calling automates the data transfer process, allowing the user to download data from a number of monitoring sites at prescribed intervals. Batch programs can also be written to include data authentication routines. The data logger manufacturer should be consulted to define the compatibility of its equipment with this feature. A single personal computer can communicate with a larger number of sites in the call out mode compared to the phone home mode.
- Phone home - automatically calls the central computer to transfer data at prescribed intervals. Sufficient time must be allocated for each call to account for a normal data transfer time and several extra calls for failed transfer attempts. The newest generation of data loggers use the internet to send data out as attached email files. This allows for simultaneous data transfer from multiple sites. In addition, the data can be downloaded to more than one computer, providing greater data security and convenience.

**Data storage devices** are part of every electronic data logger. Some data loggers have a fixed internal program that cannot be altered; others are user interactive and can be programmed for a specific task. This program, and the data buffer, are usually stored in volatile memory. Their drawback is that they need a continuous power source to retain data. Data loggers that incorporate the use of internal backup batteries or use non-volatile memory are available. They are preferred because data cannot be lost due to low battery voltage. Data processing and storage methods vary according to the data logger. The data values are stored in one of two memory formats.

- **Ring Memory:** In this format, data archiving is unceasing, but once the existing memory is filled to capacity, the newest data record is written over the oldest. The data set must be retrieved before the memory capacity of the storage device is reached.
- **Fill and Stop Memory**: In this formation, once the memory is filled to capacity, no further data are archived. This effectively stops the data logging process until more memory becomes available. The device must be replaced or downloaded and erased before the data logger can archive new data.

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

The most common data storage options are presented in the table above.

**Power sources** are required to support data loggers. There are a variety of options:

- **Household batteries** - The newest generation of loggers employ low-power electronic components whose operation can be sustained by common household batteries for six months to a year. The systems are normally dependable, but if the batteries fail then data will be lost. Furthermore, the power is not adequate for towers with heated sensors or other special power needs. To address these issues, the loggers' batteries are often augmented by another power source.
- **Lead acid battery + solar panel** - for more reliable long-term operation as well as for meeting larger power needs. 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. It is also recommended that newer battery designs that encapsulate the acid into a gel or paste to prevent spills, called non-spill or gel batteries, be used. The solar panel must be large enough to operate the monitoring system and keep the battery

charged during the worst expected conditions (usually in winter). To avoid outages that may cause data loss, it is recommended that the solar and storage system be designed for at least seven days of autonomous operation (without recharging).

- **AC power** (through a power transformer) should be used as the direct source of system power only if a battery backup is available. In this case, you should use AC power to trickle charge a storage battery that provides power to the data logger. Be sure to install a surge/spike suppression device to protect the system from electrical transients. In addition, ensure that both systems are properly tied to a common earth ground.

## Towers and sensor supporting hardware

**Towers** - two basic tower types: tubular and lattice and they can be tilt-up, telescoping, or fixed. Apart from the self-supporting lattice tower, all others use guy cables to stabilize the tower. For most new sites, tubular, tilt-up towers are suggested because they are fairly easy to install, they entail minimal ground preparation, and they are reasonably cheap. The main exception is where tall towers (more than 60m high) are required. Towers necessitate:

- Established height adequate to accomplish the highest measurement level.
- Capable to endure wind and ice loading extremes anticipated for the location.
- Physically steady to reduce wind-induced vibration.
- Guy wires safeguarded with the correct anchor type, which must match soil conditions of the site.
- Fitted out with lightning security measures including lightning rod, cable, and grounding rod.
- Be protected against vandalism and unauthorized tower climbing.
- Have all ground-level components visibly marked to evade collision hazards.
- Be sheltered against corrosion from environmental effects.
- Be protected from cattle or other grazing animals.

**Sensor Support Hardware** - includes the masts (vertical extensions) and mounting booms (horizontal extensions). Both must situate the sensor away from the support tower to diminish any effect on the measured parameter caused by the tower and the mounting hardware itself. Sensor support hardware necessitates to be:

- Capable of enduring wind and ice loading extremes expected for the location.
- Physically steady to reduce wind-induced vibration.
- Correctly oriented into prevailing wind and secured to the tower.
- Secured against corrosion from environmental effects.
- Not block the sensor housing drainage hole. Water accumulation and expansion during freezing conditions will likely damage the internal sensor components. Tubular (hollow) sensor masts should be used instead of solid stock material.

## Ground-based remote remote sensing devices

As wind turbines become higher and the magnitude and complexity of wind projects increases, there is a need for wind resource data from greater heights and in more locations across a project area. Ground-based remote sensing, which includes sodar (sonic detection and ranging) and lidar (light detection and ranging), can help meet this necessity. These instruments define the wind profile to heights of 150m or more above ground, well beyond the reach of tilt-up towers. In settings where fixed masts are excessively costly or not technically possible, they may be the exclusive source of wind measurements. Normally, they are used in combination with fixed masts, which remain the standard for resource assessment. While the practice of depending on solely on remotely sensed data is unusual at present, it is likely to become more common as the cost of the technology decreases, its accuracy and reliability improve, and experience with it grows.

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

Both sodar and lidar measure the wind very differently from conventional anemometry, as they measure the wind speed within a volume of air rather than at a point. Also they record a vector average speed rather than a scalar average speed. Remote sensing units also behave differently from anemometers under precipitation, in turbulence, and where vertical winds are significant; and their performance can be affected by variations in temperature, complex terrain, and other factors.

**Sodar (sonic detection and ranging)**

Sodar is an instrument that measures wind speed and direction by using sound waves. It is able to measure wind speed by taking advantage of the Doppler shift phenomenon, which refers to the apparent change in frequency of an acoustic signal that is perceived by a fixed observer relative to the moving source. High frequency (typically 4500 Hz) acoustic signals are emitted from the sodar in three directions, one beam in the vertical and two orthogonal beams tilted approximately 17degrees from vertical. The acoustic waves are reflected off moving, turbulent layers of air in the atmosphere thereby causing a portion of the signal to return to the sodar. The reflected signals are then measured by the sodar and an FFT (Fast Fourier Transform) is performed to analyse the frequency content of the signal. The Doppler-shifted frequency is calculated at a range of heights (up to 200m) in each direction and the vector wind speed can then be calculated. The measurements are averaged over time at set intervals, generally every 30 minutes. Sodar measures the change in frequency of sound waves, and provides information about speed and direction of the wind. Sodar can measure wind speed as a function of height and is relatively easy to transport and assemble, and the technology is very appealing.

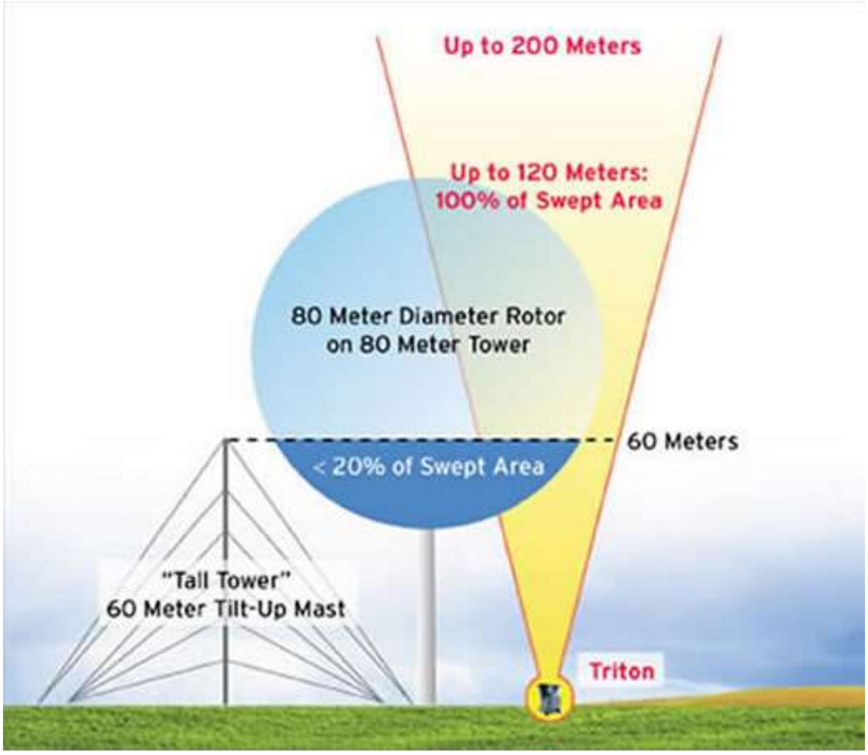


Figure 7 How sodar works. [27]

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

The power supply should be plenty to sustain unceasing 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 consume more power than most monitoring towers.

Sodar systems can call for more complex 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 extra analyses to perform to attain precise results. Further analytical effort may also be necessary in complex flow conditions to achieve readings comparable to anemometer readings. Thus it is suggested

[27] https://www.umass.edu/windenergy/research/topics/tools/hardware/sodar

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.

To prevent noise echoes that may harm data quality, sodars should be placed no closer to obstacles, such as meteorological masts, trees, or buildings, than the height of the obstacle. Because the beeping or chirping can disturb people living nearby, the sodar should be sited at least 350m from homes, and at least 500m from homes in open, flat terrain.

**Lidar (Light detection and ranging)**

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

Two distinct types of lidar currently exist for wind resource assessment.

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

A typical profiling lidar system is equipped with one or more laser emitters and receivers, an on-board computer encompassing the operating and data processing software (including self-diagnostics), environmental controls (generally, active heating and cooling), and a combined data storage and communications package. While most lidars come equipped to accept AC grid power and have on-board battery back-up in case of a grid outage, a remote power supply must be acquired or custom-built for autonomous operation away from the grid. Like sodar profilers, lidar units can be trailer-mounted for transport and may be partially enclosed for security or environmental protection; most, however, are sold by the manufacturer as stand-alone units. Lidars designed for wind energy applications came on the scene after sodars and are considerably more expensive, but nonetheless, their popularity is growing.

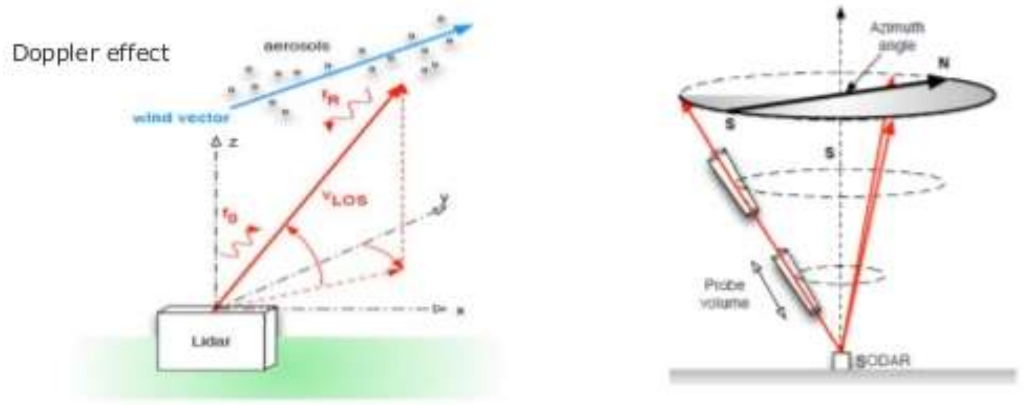


Figure 8 Lidar vs Sodara, how they work.

## Measurement system accuracy and realiabiltiy

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.

**Accuracy** - determined by the least accurate component of a system and is subjective by its complexity, the total number of components or links. The measurement of wind speed, for example, requires that several components (sensor, cabling, and data logger), each potentially contributing to a possible inaccuracy of the measured parameter. The combination of these errors will define the system error for that parameter. Errors contributed by the physical subsystem (sensors) represent the main concern, because those associated with the electronic subsystem (data logger, signal conditioner, and associated wiring and connectors) are typically negligible (less than 0.1%). System error is inaccuracy between the measurement reported and the accepted standard (or true value). Accuracy is typically expressed in three ways:

- As a difference - *(Measured Value - Accepted Standard Value)*
- A difference stated as a percentage of the accepted standard value calculated as – *[(Measured value- accepted standard value/accepted standard value)] *100*
- An agreement ratio stated as a percentage of the accepted standard value calculated as - *(measured value/accepted standard value)*100*

**Reliability** - the measure of a system's ability to constantly provide valid data for a parameter over its measurement range. The best indication of a product's reliability is its performance history. Comprehensive quality assurance procedures and redundant sensors are important ways to maintain high system reliability.

# Installation of monitoring stations

As soon as the site selection process is completed, the necessary equipment acquired, and all required permits have been obtained the installation phase of the monitoring programme can commence.

## Equipment

### Equipment Procurement

The first step in the process is to procure the equipment that will be needed to meet the objectives of the wind monitoring program, as defined in the measurement plan. This practice often includes compromises between cost, convenience, and performance. At this initial phase of project development, budgets can be constricted, leading to a desire to cut back on equipment procurement. Cost is always a vital concern, but if a monitoring program is planned with cost as an utmost importance it may be unproductive.

Matters specific to the wind monitoring program that should be incorporated in the equipment procurement process are:[28]

- Equipment and sensor specification list.
- Sensor types and quantities, including spares, the required mounting booms, cables, and hardware for each sensor.
- Tower type and height.
- Measurement parameters and heights.
- Sampling and recording intervals.
- Data logger processing requirements: hourly average and standard deviation, plus daily maximum and minimum values. Requirements and number and types of data channels required (which may affect the choice of logger model and manufacturer).
- Sensor calibration documentation.
- Environmental consideration of the anticipated conditions for the sites should be investigated to ensure that the specified equipment will perform reliably throughout the year.
- Data logger type: manual or telecommunication.
- Price quotes for equipment packages meeting the program's objectives.

[28] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.

- Soil type for proper anchor selection.
- Warranty information.
- Product support.
- Date of delivery.

**Equipment receipt testing**[29]

To swiftly determine and resolve problems, you should guarantee that all system components are comprehensively scrutinised and tested before they are fitted. Document your inspection findings, and return modules that do not meet specifications to the manufacturer for replacement. To save time on installation it is a good idea to assemble the components you can in-house, as this will save time and can be very helpful if extreme weather is a factor.

**Field preparation**[30]

Field preparation procedures include:

- Allocate site designation numbers.
- Enter all relevant site and sensor information on a Site Information Log (If required, program the data logger with the site and sensor information (slopes and offsets).
- Install the data logger's data management software on a personal computer and enter the required information.
- Enter accurate date and time into the data logger.
- Insert data logger's data storage card or applicable storage device.
- To save valuable field installation time, assemble as many components in-house as possible. For example, sensors can be pre-wired and mounted on their booms.
- Properly package all equipment for safe transport to the field.
- Pack all proper tools needed in the field.
- Include at least one spare of each component, when practical. The number of spares is contingent on the amount of wear the equipment is anticipated to undergo, as well as the projected lead time to get 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.

## Tower Installation

Identification of the true north is crucial for interpreting direction data, and is also valuable during the tower layout and installation. Frequently, directional errors arise as a result of confusion between magnetic and true north. Magnetic north is what a magnetic compass

[29] Ibid 27
[30] Ibid 27

reads; true north is the direction along the local line of longitude to the North Pole. Fortunately, these days, most GPS receivers can indicate true north, hence removing the need to consider magnetic north at all.

People on site for the installation may include:

- The mast installation team - should consist of at least one experienced installer. The quality of the data collected will largely depend on the quality of the installation. The team should consist of at least two people, with one assigned a supervisory role. This will allow for a heightened degree of efficiency and safety.
- The personnel responsible for the site's selection may not always be involved in the installation process. If this is the case, it is important that the installation team leader obtain all pertinent site information, including the latitude and longitude (verifiable with a GPS receiver), local magnetic declination, prevailing wind direction, and road maps, as well as topographic maps and site photographs that show the exact tower location.
- A backhoe operator.
- An instrument and system installer, usually a consultant wind engineer or electronics technician.
- The landowner.
- The developer.

**New tilt-up towers**

The tower should be laid out based on safety considerations and ease of installation. Towers can be erected almost anywhere, but the task is much easier if the terrain is relatively flat and free of trees. If the tower is erected on a slope or uneven ground, the guy wires may need to be adjusted often as the tower is raised. If the tower is erected in a wooded area, enough clearance must exist for the guy wires as the tower is raised. For example, a 60m tilt-up tower is guyed in four directions from the tower's base. The outermost guy anchor at each corner is 50m from the base and the four anchor points form a square roughly 71m on a side. When the tower is lying flat, it extends about 10meters, which produces a kite-shaped footprint, with two sides of 71m and two sides of at least 80m. The guy anchors should be located at each of the four cardinal directions and the tower raised along one of these directions, preferably as near to the prevailing wind direction as possible.

The figure below demonstrates the footprint of a tilt-up tower. In this example, the prevailing wind direction is assumed to be from the southwest. The "X" marks indicate anchor points. The orange dashes represent the guy wires as the tower is being raised, and the black lines indicate the path of the guy wires when the tower is fully erected.

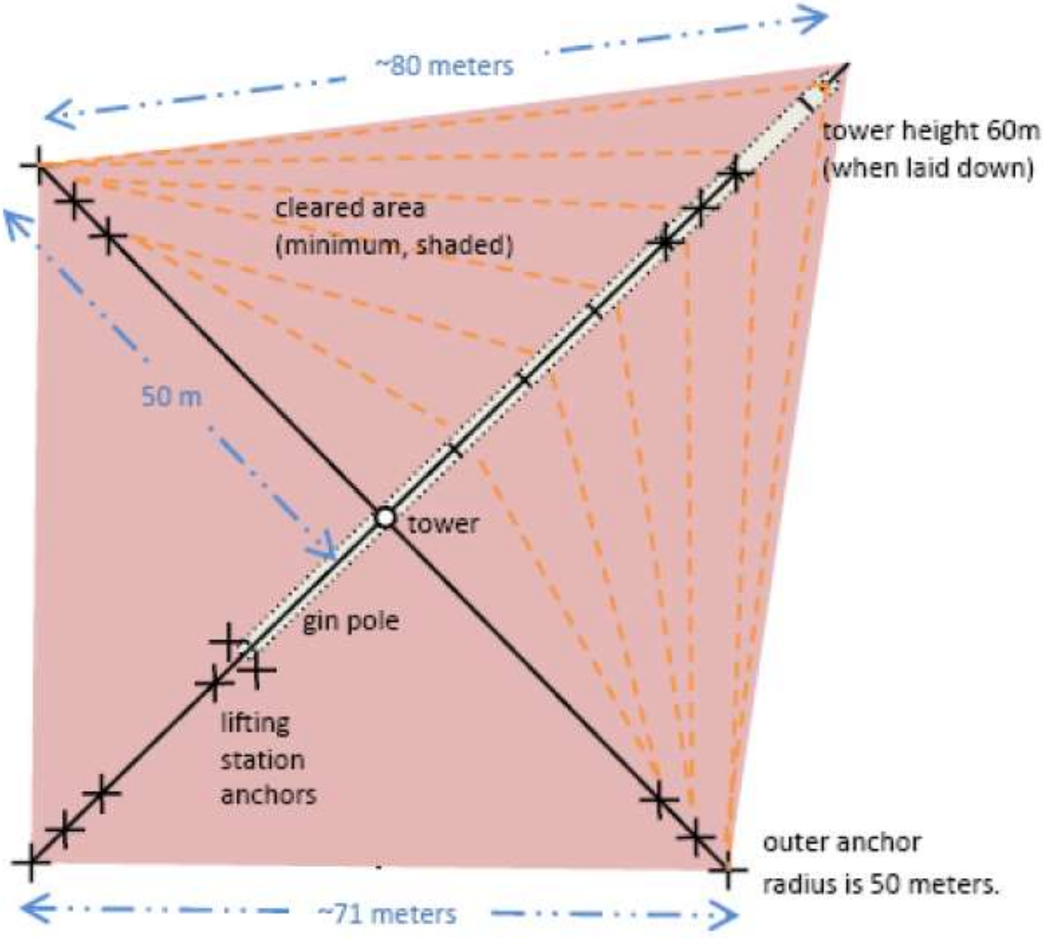


Figure 9 The footprint of a tilt-up tower [31]

It is suggested that the guy anchors should be situated at four of the eight primary directions (N, NE, E, SE, S, SW, W, NW) with respect to true north, and that one of these directions be aligned as closely as possible with the prevailing wind direction. The advantages of this approach are that it is easy to verify the orientations of the sensor booms by taking a bearing from the prone mast, and raising the tower into (or lowering it away from) the prevailing wind direction. This offers a comfortable degree of steadiness by upholding the lifting guy wires in constant tension.

**Anchoring system**

The choice of anchoring system is vital as. Tilt-up towers are secured and controlled with them and also control the tension on the guy wires at all times. Anchors should be carefully selected and installed to ensure stability.

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[31] Wind Resource Assessment Handbook, NUSERDA, 2010.

- **Anchor selection** - choice of anchoring system is contingent on the soil characteristics at each site. This should have been determined during the initial site investigation. Note that the load-carrying capacity of the soil can vary. For example, saturated soil from a winter thaw may have a much reduced carrying capacity. A mismatch between the anchor type and soil conditions could cause the anchor to fail and tower to collapse. The table below offers guidelines for selecting and installing an anchor system. Consult with the tower manufacturer if you require additional guidance.

| **Soil Type and Recommended Anchoring System** | | |
|---|---|---|
| **Soil Type** | **Anchor Type** | **Installation Method** |
| Loose to firm sand, gravel, or clay | Screw-in | Screw-in with crowbar |
| Soil with rocks | Arrowhead | Sledge or jack-hammer |
| Solid Rock | Pin / Rock Anchors | Drill hole and secure with epoxy/expand with crowbar |

Figure [32]

- **Anchor Installation** - the installation of each guy anchor and lifting station anchor should follow the manufacturer's instructions. The lifting station anchor warrants special attention. Normally a winch and pulley system is connected to this anchor to service a tower. During tower lifting and lowering, this anchor will carry all of the tower load and is thus under great stress. The greatest loads occur when the tower is just raised, above the ground. Since the magnitude of this force is well known, the behaviour of the selected anchors in the site soil conditions can be evaluated. If the anchors do not seem sufficient for the soil conditions, alternative anchoring should be identified and implemented prior to tower installation. If the holding capacity of this anchoring system is insufficient, the anchor will creep and the tower will fall. For this reason, the lifting anchor station should be secured with at least twice as many anchors as used at the guy anchor stations. As an added precaution, secure these anchors to a vehicle bumper.
- **Guy Wires** - it has to be guarantee that all guy wire tension alterations are coordinated as under proper tension the guy wires keep the tower system in equilibrium and thus vertical. This is essential to properly align the wind speed and direction sensors. Refer to the manufacturer's instructions for guy wire tension

[32] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.

recommendations. It is desirable to visibly mark with a reflective material at each anchor station to alert pedestrians or vehicle operators. If animals graze at the site, a fence may be necessary to protect the guy stations and tower.

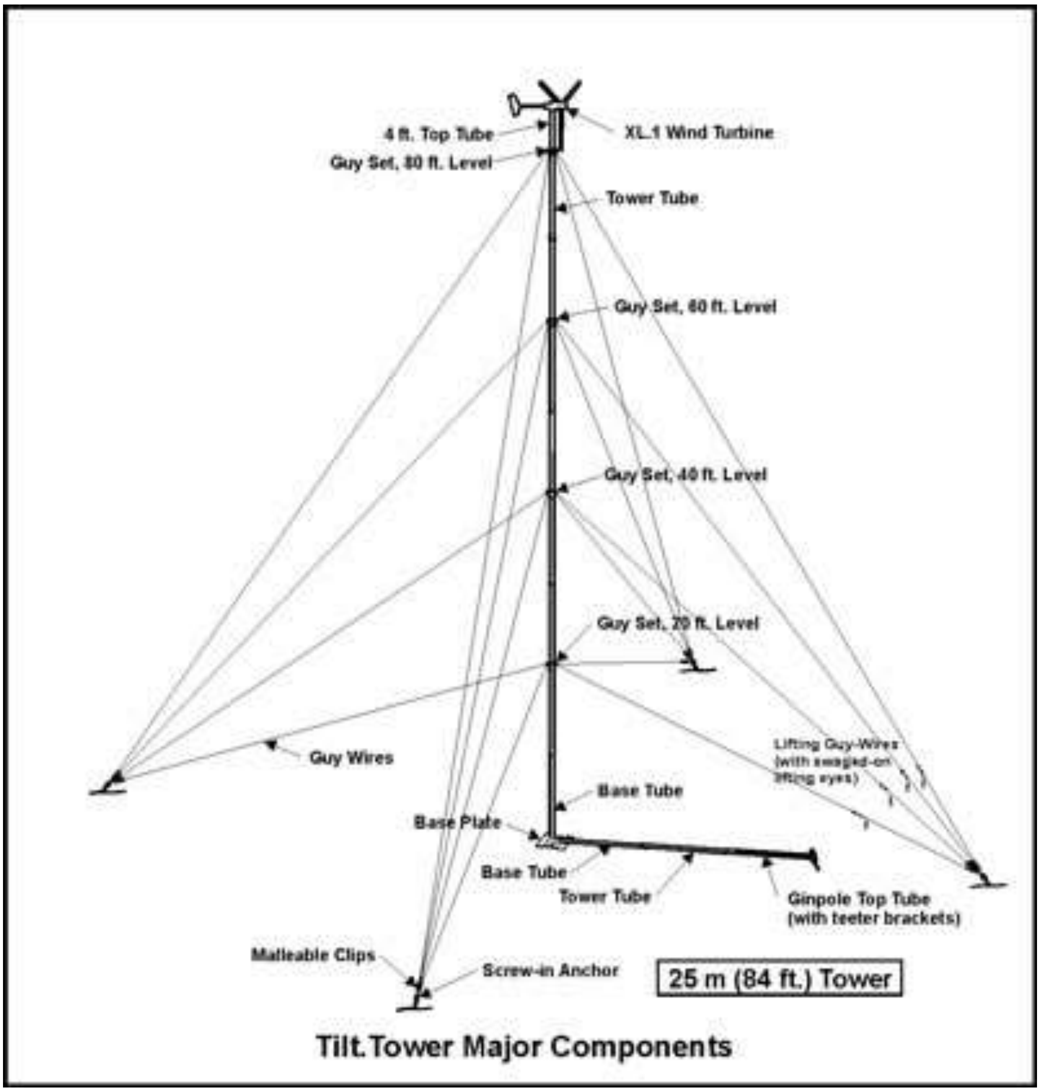



Figure 10 Tilt tower major components. [33]

As shown in the figure above, the tower is guyed in four directions. The tower is guyed at vertical intervals of approximately 6 meters as the tower height is 25m. The monitoring tower is best installed on level ground, but can be installed on slopes or uneven terrain provided that the base and the anchors on the tilt-axis can be kept fairly level. After assembly of the tower, wind turbine, and tower wiring on the ground, the tower and turbine are tilted-up to the vertical position using a winch (optional) or a vehicle. A winch is preferred because of the greater control they afford. The towers are provided with a lever arm, called a gin-pole, which runs from the base towards one of the guy anchors. The gin-

[33] http://www.survivalunlimited.com/towers/xl1tower.htm

pole converts the pulling force on the pull-up rope or cable into a lifting force on the turbine and tower.

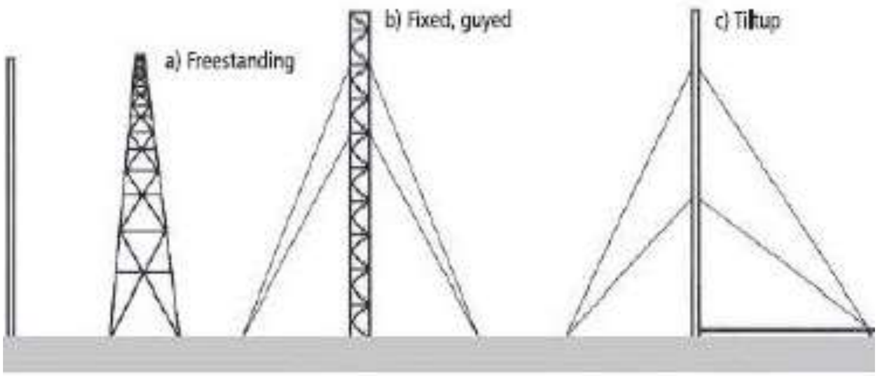
## New Lattice Towers[34]

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

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

The figure below shows the thee different types of towers that can be used in wind monitoring campaign.

1) Freestanding
   a) Lattice
   b) Monopole
2) Fixed Guyed
   a) Lattice
   b) Tubular (typically homebuilt)
3) Tilt-up
   a) Guyed tubular
   b) Guyed lattice




[34] Wind Resource Assessment Handbook, NUSERDA, 2010.

Figure 11 Freestanding, fixed guyed and tilt-up tower. [35]

## Sensor and equipment installation

Wind sensors must be fixed onto the tower with support hardware in a way that diminishes any effect on the measured parameter caused by the tower, mounting hardware, and other equipment and sensors. This can be realized by following to the subsequent guidelines and referring to specific manufacturers' instructions.

**Wind Speed and Direction Sensors**[36][37]

The number of sensors is subject to the height of the tower. For a 50m or 60m tower, three anemometer heights are normally used, and taller towers may have four, while commonly vanes are deployed at two heights. The following general guidelines govern the selection of anemometer heights and are applicable to most towers:

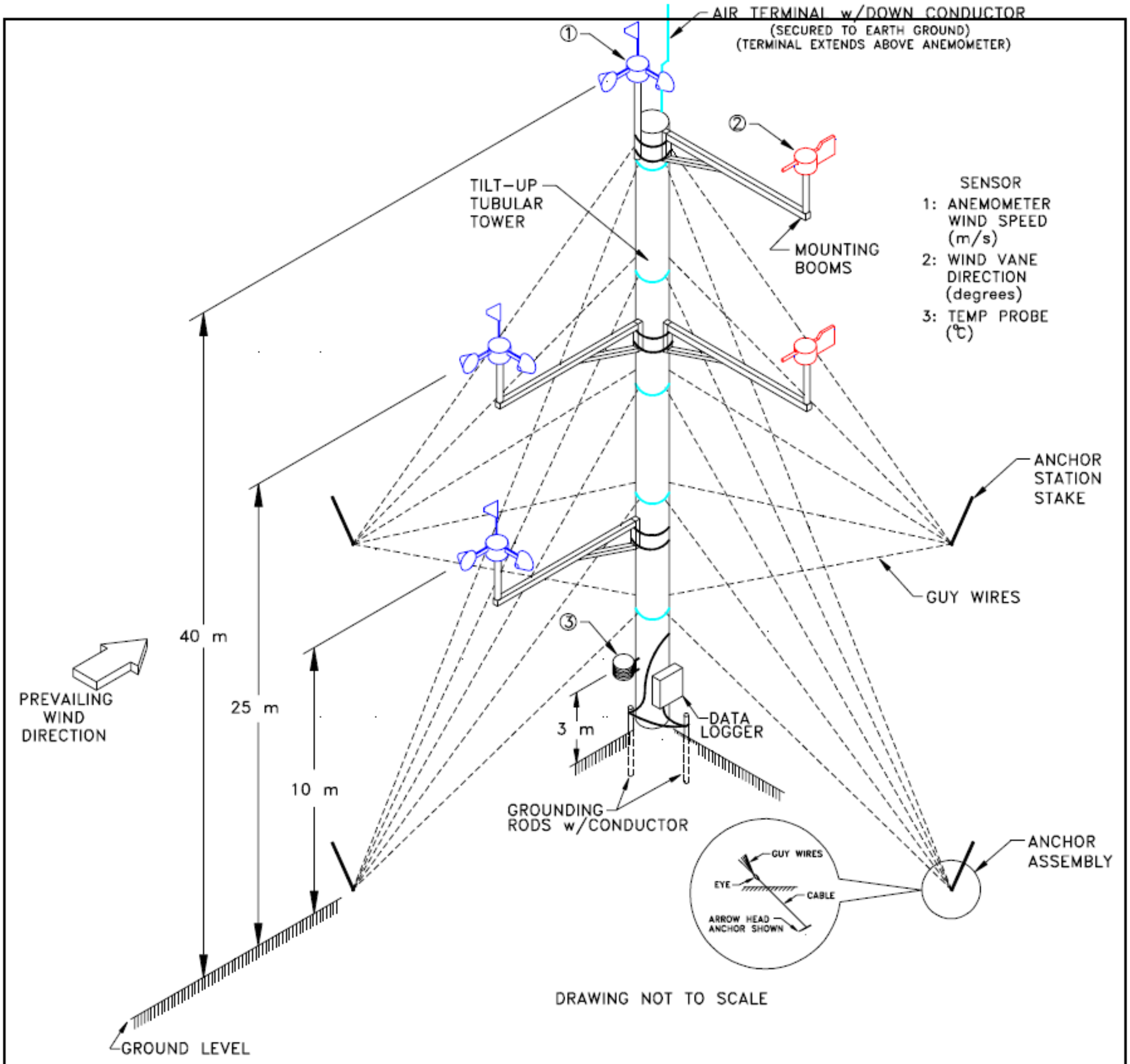
- The total number of sensor levels is contingent on the overall height of the tower. One of the heights should be as close as possible to the anticipated turbine hub height. Mount the upper-level sensors at least 0.3m above the tower top to minimize potential tower shading effects.
- The heights should be as widely separated as possible to reduce uncertainty in shear. Height ratio of at least 1:66 between the top and bottom anemometers is suggested.
    - The topmost anemometers, if mounted on horizontal booms, should be at least 10 tower diameters below the top of the tower to avoid effects of flow over the top (known as 3D flow effects).
    - The bottom anemometers should be mounted adequately high above ground to evade undue influence by trees, buildings, and other features, and to measure the wind near the bottom of the turbine rotor plane.
- Orient sensors mounted off the tower side into the prevailing wind direction, or, if there is more than one prevailing direction, in a direction that minimizes the probability of tower and sensor shadow effects.
- Sensor drainage holes must not be blocked by the vertical mounting hardware to prevent internal freezing damage during cold weather. Tubing, not solid stock masts, should be used.
- The wind vane must be oriented so its deadband position is not directed towards the prevailing wind. The deadband should be positioned at least 90° away from the prevailing wind direction, preferably in a principle direction. The deadband orientation must be known and documented for the data logger or analysis software

[35] https://newgreenbusinessideas.blogspot.com/search/label/Freestanding%20Towers
[36] Wind Resource Assessment Handbook, NUSERDA, 2010.
[37] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.

to report the correct wind direction. Consult the data logger manufacturer's requirements for reporting the deadband position.

- Confirm the deadband position of the wind vane once the tower is raised. If it has been aligned with the mounting boom arm, verification can be accomplished with a sighting compass to a high degree of accuracy.
- At projects with multiple monitoring stations (met towers or remote sensing), it is useful to match the monitoring heights between the stations to the greatest extent possible to facilitate comparisons between the stations.

The figure below shows a sample installation configuration.



Sample Installation

Figure 12 Sample installation configuration [38]

## Temperature sensor

A protected temperature sensor should be fixed on a horizontal boom at least one tower diameter from the tower face to reduce the tower's influence on air temperature. The sensor should be well exposed to the prevailing winds to ensure sufficient ventilation at most times. If possible, fix the sensors on the northern side of the tower to limit heating from direct solar gain and decrease the effect of thermal radiation from the tower's surface.

## 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. Desiccant packs 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 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. Mount the enclosure at an adequate tower height to allow for above average snow depth and to discourage vandalism. If related, locate the solar panel above the enclosure to avoid shading, oriented south and near vertical to minimize dirt build-up and maximize power during the winter's low sun angle. Where applicable, the cellular communication antenna should be attached at an accessible height, usually right above the data logger enclosure.

## Sensor connecting and cabling

Refer to the manufacturer's instructions for the proper sensor and data logger wiring configurations. Seal sensor terminal connections with silicone caulking and protect from direct exposure with rubber boots. Wrap sensor cabling along the length of the tower and secure it with UV resistant wire ties or electrical tape. If not installed by the manufacturer, consider installing Metal Oxide Varistors (MOVs) across each anemometer and wind vane terminal for added electrical transient protection. Where chafing can happen between the sensor wires and supports (such as tilt-up tower anchor collars), the wires should be sheltered and safeguarded aptly.

## Grounding and lightning protection

Most tower and data logger manufacturers provide grounding kits. Nevertheless, different monitoring areas may have different requirements. Examine the incidence of lightning activity in the site's locality. For high frequency areas, take the conformist tactic and

[38] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997.

increase the grounding system capabilities. Additional protective equipment can often be purchased from the data logger manufacturer or supplemented with common materials found at a hardware store.

## Site commissioning

All equipment should be tested to be sure it is operating before a tower is raised and this should be repeated once the installation is complete. Having spare equipment on hand makes repairs easy if problems are found during these functional tests. Recommended actions:

- Confirm that all sensors are reporting reasonable values.
- Validate that all system power sources are operating.
- Test required data logger programming inputs, including site number, date, time, sensor slope and offset values, and deadband orientations.
- Proof 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.
- Document the departure time and all other pertinent observations.

## Documentation

A comprehensive and thorough record of all site characteristics, as well as data logger, sensor, and support hardware information, should be preserved in a Site Information Log (see the next page for an example). The following main topics should be included:[39]

- Site Description - include a unique site designation number, a copy of a USGS map showing the location and elevation of the site, latitude and longitude, installation date, and commission time. The coordinates of the site should be determined or confirmed using a GPS receiver during the site selection or installation process. Normally, coordinates should be expressed to an accuracy of less than 0.1 minute (at least 100m) in latitude and longitude and at least 10m in elevation. This should remove errors caused by accidentally marking sites in the wrong place on a map and recording incorrect coordinates taken from the map.

[39] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL

- Site Equipment List: For all equipment (data logger, sensors, and support hardware), document the manufacturer, model, and serial numbers as well as the mounting height and directional orientation (including direction of deadbands, cellular antenna, and solar panel). Sensor information should include slope and offset values and data logger terminal number connections.
- Telecommunication information: pertinent cellular phone or satellite link programming information should be documented.
- Contact Information: relevant landowner and cellular/satellite phone company contact information should be listed.

**SAMPLE SITE INFORMATION LOG**
**(Cellular Site)**

**Form Revision Date:**

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

| Site Equipment List | | | | | | |
|---|---|---|---|---|---|---|
| Equipment Description | Mounting Height | Serial Number | Sensor Slope | Sensor Offset | Logger Terminal Number | Boom Direction (Vane Deadband) |
| | | | | | | |
| | | | | | | |
| | | | | | | |
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| | | | | | | |

| Telecommunication Information | |
|---|---|
| ESN # | |
| Carrier | |
| Phone Number | |
| SYSID | |
| LOCAL | |
| MINMARK | |
| IPCH | |
| ACCOLC | |
| PRESYS | |
| GROUP | |
| Activation Date | |

| Contact Information | |
|---|---|
| Land Owner Name | |
| • Address | |
| • Phone Number | |
| Cellular Company | |
| • Phone Number | |
| • Contact Person | |
| • Contact's Extension | |

[40]

# Site operation and maintanance

During the course of a wind resource assessment project, the integrity of all system components must be sustained and recorded to guarantee smooth and constant data collection. Meteorological instruments, for example, require periodic calibration, precautionary maintenance, and on-site visual inspections if the data is to be correct and comprehensive. There is a need to enact an operation and maintenance plan that integrates numerous quality control and quality assurance measures, which will be the starting point for procedural guidelines for all program personnel. Personnel must be methodically taught in all aspects of the operation and maintenance program, including a working knowledge of all monitoring system equipment.

The realisation of any operation and maintenance program relies on the plan and on the employees allocated to carry out the set tasks. They will be the eyes of the wind resource network and responsible for documenting and explaining any periods of lost data; thus they need to be observant and have good problem-solving abilities. There should be both scheduled and unscheduled site visits, procedures, checklists and logs, calibration checks, and a spare parts inventory. Guidelines to develop such a program are provided in this section.[41]

## Site visits

It is suggested that site visits be conducted according to a regular schedule. The regularity of scheduled visits depends in part on the data recovery method. If the data is retrieved remotely and screened every week or every other week, then the site may have to be visited no more often than once every several months for visual inspection and routine maintenance.  If data retrieval is manual, site visits should be conducted at least bi-weekly. Site visits should be planned according to the capacity of the storage device are promptly detected through visual inspection or data screening. The appropriate frequency is recommended to meet the 90% data recovery objective. Unscheduled might be needed if there is a sensor malfunction found during routine data screening, or it may be feared that

[40] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997

[41] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997

the tower or its equipment was damaged in a storm or under severe icing conditions. To minimize potential data loss, such visits should be carried out as soon as possible after a problem is suspected. Both the program budget and staffing plans should anticipate at least one unscheduled site visit each year.[42]

## Operation and maintenance

The operation and maintenance plan should be documented in a *Site Operation and Maintenance Guidebook*. The objective is to deliver systematic and clear processes for scheduled and unscheduled operation and maintenance needs for field personnel. The preferred version of the guidebook, is a step-by-step approach in conjunction with task completion checklists and site visit logs. Components that need to be in included in the guidebook:

**Project description and operation and maintenance values** - define the project and its overall objectives. The significance of the technician's role in the project's realisation through upholding data quality and inclusiveness should be emphasised.

**System elements accounts** - the fundamentals of all system components should be detailed carefully in order to guarantee correct installation, and to perform system checks and operation and maintenance procedures. A brief description of all instruments (anemometers, wind vanes, temperature probes, data logger, etc.) and how they work should be provided, including thorough element information, such as manufacturer's manuals.

**Routine instrument care guidelines** [43]- they should be provided for all instruments that require routine maintenance. Some anemometer models require periodic bearing replacement. If sensors are replaced, all pertinent information, including serial numbers and calibration values, should be recorded.

- **Anchor Condition**:
  - Check for signs of rust or damage.
  - Evaluate movement of the anchors over time.
  - Validate 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.

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[42] Wind Resource Assessment Handbook, NUSERDA, 2010
[43] Wind Resource Assessment Handbook, NUSERDA, 2010

        - Inspect the wires and connection points for signs of rust or corrosion.
        - Ensure 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.
        - Examine the baseplate or foundation to guarantee that it is not sinking or distorted, and is free from damage.
    - **Grounding System:**
        - Verify that the grounding system is connected properly and the electrical contacts are in good condition.
    - **Sensors:**
        - Examine the booms and stubmasts to evaluate their condition and levelness.
        - Authorize that the sensors are at the expected monitoring heights and orientations.
        - Change any sensors that have shown signs of failure through data analysis.
        - Wind vanes and anemometers should be replaced on a regular basis as part of a precautionary maintenance plan. A replacement schedule that minimizes discontinuities is suggested.
        - Some anemometer types require periodic refurbishment, such as ball bearing replacement and recalibration.
    - **Data Acquisition System**:
        - Examine 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 avoid losing connection to the sensors.
        - Check battery voltage and replace batteries as necessary.
        - Batteries are most often charged by a solar PV system (5 to 50W). The PV system maintenance includes cleaning and realigning solar panels and sensors. The panels and wiring/electrical connections should be checked for cracks and water resistance.
        - Refuel and test the diesel generator, if one is used.

**<u>Site Visit Procedures</u>**

- **In-house preparation**
    - Establish the object for the inspection and the precise requirements.
    - Guarantee that field staff have a complete set of tools, supplies, equipment manuals, and spare parts to complete all tasks. The checklist specifying the required tools and supplies will be handy. This list should include all equipment

necessary to download the site data, such as laptop computers with associated cables and special hardware.
- Implement 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.
- Define the number of people necessary for the site visit. For safety, tower climbing requires two or more people.
- Have field staff notify management of where they plan to be and when they expect to return.

- **On site procedures**[44] [45]
  - Retrieving the raw data from the data logger upon arrival and before conducting any other work. This is essential as it will diminish the risk of potential data loss from operator error, static discharges, or electrical surges during handling or checking of system components.
  - No matter the purpose of the visit, each visit should include a comprehensive visual inspection (with binoculars or digital camera), as well as testing when appropriate, to identify damaged or faulty components. The inspection should include: data logger, sensors, communication system, grounding system, wiring and connections, power supply, support booms, tower components (for guyed tower systems this includes anchors, guy wire tension, and tower vertical orientation).
  - Develop general guidelines before the first site visit for scheduled component replacement batteries, calibration, and troubleshooting.
  - The instantaneous data logger readings should be scanned to validate that all measured values are realistic.
  - The Site Visit Checklist should be filled out to guarantee that all operation and maintenance tasks have been concluded and the essential 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). This simple but valuable test will ensure the system is operating properly and the remote communication system (antenna direction and phone connections) was not by accidentally altered.

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[45] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997

- Ensure the data logger has been returned to the proper long-term system power mode because this may reduce battery life and may cause data loss.
- Always secure the data logger enclosure with a good quality padlock.
- Record the departure time and verify that all work performed and observations made have been recorded on the Site Visit Checklist.

# Data collection and management

The chief objective of the data collection and management process is to make the meteorological measurements accessible for investigation while guarding them from tampering and loss. The data collection and handling must include procedure that delivers a high level of data protection. In general, the procedures should comply with those specified by the data logger manufacturer and reflect good common sense.

## Raw data storage

Raw data are data that has not been exposed to a substantiation or certification process are typically stored by the data logger in binary format. Data storage types in the table below.

| Storage Device | Description | Download Method/ Needs |
|---|---|---|
| **Memory Card** | Independent memory chips in numerous formats (e.g., MMC, SD, microSD, SDHC, memory Stick, USB flash drive) used in cameras and other devices | Read and erased onsite or replaced. Reading device and software required. |
| **Solid State Module** | Integrated electronic device that directly interfaces with the data logger. | Read and erased onsite or replaced. Reading device and software required. |
| **Data Card** | Programmable read write device that plugs into a special data logger socket. | Read and erased on-site or replaced. Reading device and software required. |
| **EEPROM Data Chip** | An integrated circuit chip incorporating an electrically erasable and programmable read only memory device. | EEPROM reading device and software required. |

| | | |
|---|---|---|
| **Magnetic Media** | Familiar floppy disk or magnetic tape (i.e., cassette). | Software required reading data from the media. |
| **Portable Computer** | Laptop or notebook type computer. | Special cabling, interface device, and/or software may be required. |

**Data storage capacity** [46]

The minimum mandatory storage capability of the logger is contingent on the data retrieval interval (typically once every one or two weeks); the data-averaging interval (typically 10 minutes); the number of sensors being monitored (typically 8-to-12 on a 60m tower); and the number of parameters calculated and stored by the logger. The capacity of the data storage devices normally used today is at least 16MB, with allowance for bigger capacity if data-averaging interval is shorter. Another reason for bigger storage capacity may be if the tower is likely to be inaccessible for months at a time because of extreme and harsh weather. Then, if the telecommunications uplink fails, the logger may be called up to store data for up to several months. Manufacturers usually provide tables or methods to calculate the approximate available storage capacity (in days) for various memory configurations. Capacity estimates should also allow for delays in retrieving the data.

## Data Retrieval

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

- Personnel availability
- Travel time to site
- Year-round site accessibility
- Availability of cellular phone service
- Equipment cost
- Types of sensors
- Complexity of initial configuration
- On-site power needs
- Ease of use
- Support systems required (computers, modems, analysis and presentation software, etc.)

[46] Wind Resource Assessment Handbook, NUSERDA, 2010

**Data retrieval frequency**

An agenda of consistent site data transfers, or downloads, should be established and sustained. The maximum recommended manual download interval is bi-weekly. For remote data transfer systems, a weekly retrieval rate may suffice but a shorter interval, such as two-day, may be required to successfully transfer the large datasets associated with ten-minute data averaging.

## Data security and storage

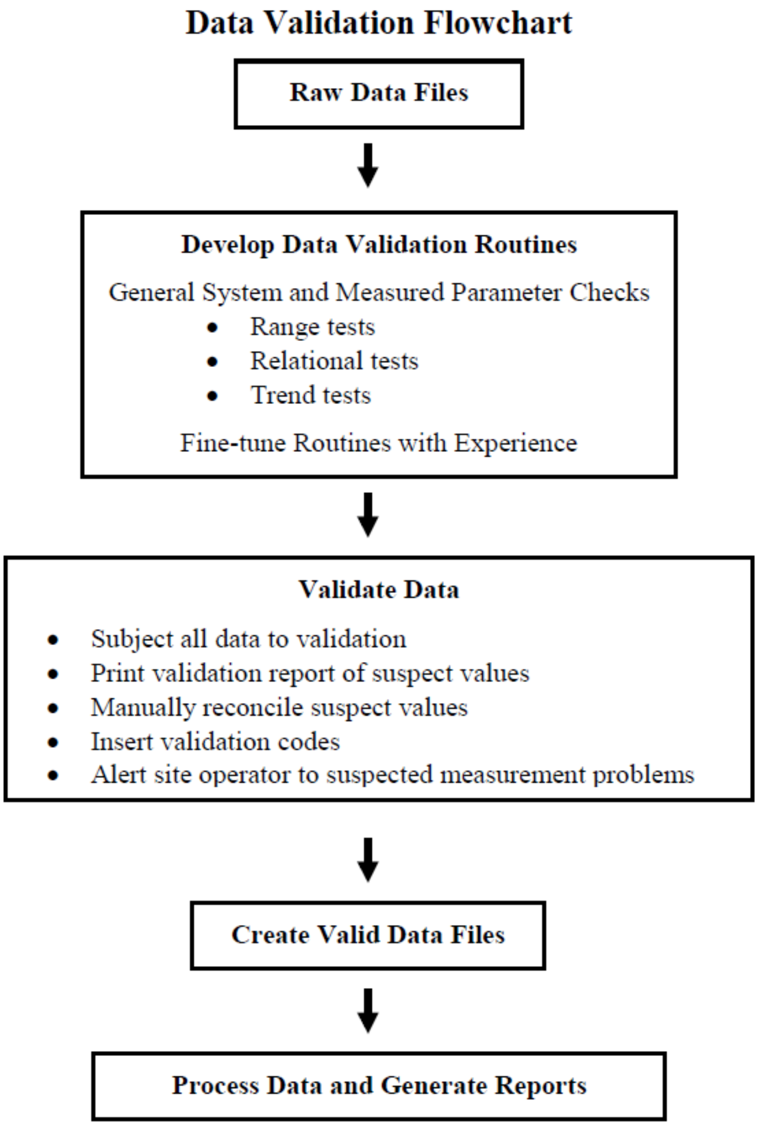
The following components and procedures are highlighted to offer guidance on minimizing the risk of data loss or alternation during the measurement program.

- Data logger - to guarantee data are protected while stored in the data logger, proper installation procedures should be followed, including grounding all equipment and using spark gaps.
- Electronic Data Collection Subsystem – aside from the data logger programming requirements, the actual data collection process requires minimal technician input.
- Computer Hardware - field data will ultimately be transmitted to a personal computer for analysis. This will be the primary location of the working database, but should not be the storage area for the archived database. Electrical surges and static discharges may damage hard drives and floppy disks. Follow the manufacturer's instructions and recommendations for all electrical connections. Make use of external hard drives to back up your data.
- Data Handling Procedures - inadequate data handling procedures may represent the highest risk for data loss, so it is imperative all employees are fully trained and understand the following:
    - Data retrieval software and computer operating system (be aware of all instances in which data can be accidentally over-written or erased).
    - Good handling practices for all data storage media. Data cards and hard disk drives should be protected from static charge, magnetic fields, and temperature extremes.
    - Computer operations and safety practices, including grounding requirements.

To reduce the risk of data loss, maintain multiple copies of the database, or backups, and store each copy in a separate location (not in the same building). Online backup services have recently become popular and are especially secure as well as convenient for frequent backups. With remote data transfers via e-mail, another, very effective data-protection strategy is to set up back-up email accounts. The e-mailed files go to different computers in different locations. Back-up the data on a schedule equal to the data retrieval interval.

# Data validation

After the wind resource measurements are collected and transferred, the next step is the quality-control phase to validate the data, to guarantee that only valid data is used in subsequent analyses and that the data is precise. The flowchart below shows the steps in validating data.



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[47] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997

Data validation is defined as the assessment of all the collected data for inclusiveness and reasonableness, and the removal of invalid values. This step transforms raw data into validated data. The validated data is then processed to produce the summary reports required for analysis. Data must be validated as soon as possible, in order to notify the site operator of a potential measurement problem, and reduce the risk of data loss or erroneous data collection.

## 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 operational file format. Most manufacturers provide the appropriate software for the data conversion.

For precise data conversion and successive analysis, the settings relating to wind vane deadband, anemometer transfer function, and time zone should be correctly entered in the conversion software. Mistakes (boom orientation, magnetic declination, and anemometers serial numbers) do come about at this stage and if not detected at the outset, can lead to significant errors in characterizing the site's wind resource. Thus, the analyst should pursue independent validation of key information, from photographs confirming 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. Calibrated anemometers should have a license 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.

A good data-handling practice insures both the raw and converted data should be well-kept in permanent archives. All subsequent data validation and analyses should be executed on copies of the converted data files.

## Data Validation methods

At present this is done with automated tools, nevertheless, a manual review is still commended. In essence there are two parts to data validation, data screening and data verification.

- **Data Screening -** uses a series of validation routines or algorithms to screen the data for suspect (questionable and erroneous) values. Algorithms commonly include relational tests, range tests, and trend tests. A suspect value warrants enquiry but is not automatically invalid. The result of this part is a data validation report (a printout) that lists the suspect values and which validation routine each value failed. Suspect records encompass values that fall outside the normal range based either on prior knowledge or information from other sensors on the same tower.

- **Data verification** -involves a case-by-case decision about what to do with the suspect values – preserve them as valid, discard them as invalid, or replace them with redundant, valid values (if available). This part is where conclusion by a competent person familiar with the monitoring equipment and local meteorology is necessary. Information that is not part of the automated screening, such as regional weather data, may also be brought into play.

The margins of data validation are the many possible causes of erroneous data: faulty or damaged sensors, loose wire connections, broken wires, damaged mounting hardware, data logger malfunctions, static discharges, sensor calibration drift, and icing conditions, among others. The goal of data validation is to identify as many substantial errors from as many causes as possible. Over identifying presents a prospect to review bad data records, while good records usually are not scrutinized further. Failing to discard even a small number of bad values can considerably prejudice a wind resource analysis, whereas excluding a moderate amount of good data rarely has such an impact. Still, care must be taken in designing the automated screening not to overwhelm the review phase with an excessive number of false positives.

**Validation routines**

Validation routines are intended to monitor each measured parameter for suspect values before they are integrated into the archived database and used for site analysis. They can be grouped into two main categories

- **General system checks** - two simple tests assess the comprehensiveness 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 is examined to see if there is any missing or out-of-sequence data.
- **Measured parameters check** - represents the heart of the data validation process and normally consists of range tests, relational tests, and trend tests.
  - Range Tests - simplest and most commonly used validation tests. The measured data is equated to permissible upper and lower limiting values. A reasonable range for most expected average wind speeds is 0 to 25 m/s. However, the calibration offset supplied with many calibrated anemometers will prevent zero values. Negative values clearly indicate a problem; speeds above 25 m/s are possible and should be verified with other information. The parameters of each range test must be set so they include nearly (but not absolutely) all of the expected values for the site. Technicians can fine-tune these parameters as they gain experience. In addition, the limits should be attuned seasonally where applicable. See below sample range test criteria.

## Sample Range Test Criteria

| *Sample Parameter | Validation Criteria |
|---|---|
| **Wind Speed: Horizontal** | |
| • Average | offset < Avg. < 25 m/s |
| • Standard Deviation | 0 < Std. Dev. < 3 m/s |
| • Maximum Gust | offset < Max. < 30 m/s |
| **Wind Direction** | |
| • Average | 0° < Avg. ≤ 360° |
| • Standard Deviation | 3° < Std. Dev. < 75° |
| • Maximum Gust | 0° < Max. ≤ 360° |
| **Temperature** | (Summer shown) |
| • Seasonal Variability | 5°C < Avg. < 40°C |
| **Solar Radiation** | (Optional: Summer shown) |
| • Average | offset ≤ Avg. < 1100 W/m² |
| **Wind Speed: Vertical** | (Optional) |
| • Average **(F/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) |
| • Average | 94 kPa < Avg. < 106 kPa |
| **ΔT** | (Optional) |
| • Average Difference | > 1.0° C (1000 hrs to 1700 hrs) |
| • Average Difference | < -1.0° C (1800 hrs to 0500 hrs) |

[48]

- Relational Tests - comparison is based on expected physical relationships between various parameters. Relational checks should ensure that physically improbable situations are not reported in the data without verification; for example, significantly higher wind speeds at the 25m level versus the 40m level. Wind speeds recorded at the same height should be similar (except when one anemometer is in shadow); wind shears between heights should fall within reasonable bounds (which may vary diurnally and seasonally). Please see the table below for an example of relational test criteria:

[48] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997

## Sample Relational Test Criteria

| *Sample Parameter | Validation Criteria |
|---|---|
| **Wind Speed: Horizontal** | |
| • Max Gust vs. Average | Max Gust ≤ 2.5 * Avg. |
| • 40 m/25 m Average Δ** | ≤ 2.0 m/s |
| • 40 m/25 m Daily Max Δ | ≤ 5 m/s |
| • 40 m/10 m Average Δ | ≤ 4 m/s |
| • 40 m/10 m Daily Max Δ | ≤ 7.5 m/s |
| **Wind Speed: Redundant** | (Optional) |
| • Average Δ | ≤ 0.5 m/s |
| • Maximum Δ | ≤ 2.0 m/s |
| **Wind Direction** | |
| • 40m/25 m Average Δ | ≤ 20° |

* All monitoring levels except where noted.
** Δ: Difference

[49]

- Trend Tests - checks are based on the rate of change in a value over time. An example of a trend that indicates an unusual circumstance and a potential problem is a change in air temperature greater than 5°C in one hour. The thresholds actually used should be adjusted as necessary to suit the site conditions. See example below.

## Sample 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 |
| **Δ Temperature** | (Optional) |
| • 3 Hour Change | Changes sign twice |

* All monitoring levels except where noted.

[50]

[49] Ibid 48
[50] Ibid 48

## Handling of suspect data

After the raw data is exposed to the automated validation checks, a reviewer should decide what to do with the suspect data records. Some suspect values may represent real, although rare, weather incidences, which should not be omitted from the resource assessment. Others may reflect sensor or logger problems and should be eliminated. Here are some guidelines for handling suspect data:

- **Prepare a validation report** – listing all the suspect data. For each data value, the report should give the reported value, the date and time of occurrence, and the validation criteria that it failed.
- **Match the data** – a competent person should scrutinise the suspect data to conclude their acceptability. Check to see whether data from different sensors on the same mast confirm the suspect reading. If a brief feature such as a large jump in wind speed is noted at one anemometer, is a similar jump seen in another? If only one sensor shows the feature, it is more likely that the data for that sensor is invalid. Invalid data should be assigned and replaced with a validation code.
- **Verify weather conditions** - use data from a variety of sources to validate weather conditions (suspected icing, large changes in wind or temperature).
- **Relationships between sensors over time** - sensor degradation happens so slowly that it is ignored if the data is only examined two weeks or a month at a time. By examining the relationships over several months or longer, the degradation becomes evident.
- **Redundant sensors** - if redundant sensors are used, substitute a rejected value from the primary sensor with a substitute one from the redundant sensor as long as the redundant sensor's data passed all the validation criteria.
- **Record** - preserve a complete record of all data validation actions for each monitoring site in a Site Data Validation Log. This document should contain the following information for each rejected and substituted value: file name; parameter type and monitoring height; date and time of flagged data; validation code assigned and explanation given for each rejected datum; the source of the substituted values.

## Data recovery

The data recovery rate is defined as the number of valid data records collected versus that possible over the reporting period and should be determined for each primary wind sensor (for all levels at each site). The method of calculation is as follows: *Data Recovery Rate = Data Records Collected / Data Records Possible * 100.* Where *Data Records Collected = Data Records Possible - Number of Invalid Records.*[51]

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[51] Ibid 48

# Data processing

Once the data validation stage is complete, the data set must be put through several data processing procedures to assess the wind resource. This comprises of calculations on the data set, as well as binning the data values into useful subsets based on the choice of averaging interval. This results in useful reports, such as summary tables and performance graphs. Data processing and reporting software are available from several sources, including data logger manufacturers and vendors of spreadsheet, database, and statistical software.

**Post- validation modifications**

Good sensors fixed properly should deliver precise measurements of wind speed, direction, and other meteorological parameters. Nonetheless, there are several factors that often need to be considered separately to correctly appraise the true free-stream speed, except for fully programmable data loggers and tower effects. Inclination, the wind shear exponent, turbulence intensity, and wind power density are not typically internal processing functions of most data loggers. These parameters can be easily calculated using a spreadsheet software application to obtain hourly and monthly averages.

- **Mean wind speed** - is time-averaged wind speed, averaged over a specified time interval. The most commonly used technique of projecting the mean wind speed from the height of observation to the turbine hub height is by means of the power law. The power law is a functional relationship between two quantities, where a relative change in one quantity results in a proportional relative change in the other quantity, independent of the initial size of those quantities: one quantity varies as a power of another. The wind profile power law is a relationship between the wind speeds at one height, and those at another. The formula:[52]

$$v_2 = v_1 \left(\frac{h_2}{h_1}\right)^{\alpha}$$

*h1* = to the top anemometer height

*h2* = hub height

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

[52] Wind Resource Assessment Handbook, NUSERDA, 2010

- **Vertical wind shear exponent** - wind shear is defined as the change in horizontal wind speed with a change in height. The wind shear exponent (α) should be determined for each site, because its magnitude is influenced by site-specific characteristics. The 1/7th power law (as used in the initial site screening) may not be applied for this purpose, as actual shear values may vary significantly from this value. Solving the power law equation for α gives:[53]

$$\alpha = \frac{Log_{10}\left[\frac{v_2}{v_1}\right]}{Log_{10}\left[\frac{z_2}{z_1}\right]}$$

Where:

*v2* = the wind speed at height *z2*

*v1* = the wind speed at height *z1*.

- **Turbulence intensity** - wind turbulence is the hasty disturbances or abnormalities in the wind speed, direction, and vertical component. It is an important site characteristic, because high turbulence levels may decrease power output and cause extreme loading on wind turbine components. The magnitude of the over-speeding depends on the sensor type and degree of turbulence. Cup anemometers are known to overestimate the wind speed in turbulent flow conditions, while prop-vane anemometers tend to underestimate the wind speed, and sonic anemometers, lacking moving parts, are insensitive to turbulence. The most common indicator of turbulence for siting purposes is the standard deviation (σ) of wind speed. Regulating this value with the mean wind speed gives the turbulence intensity (TI). This value allows for an overall assessment of a site's turbulence. TI is a relative indicator of turbulence with low levels indicated by values less than or equal to 0.10, moderate levels to 0.25, and high levels greater than 0.25. TI is defined as:

  Where

  σ = the standard deviation of wind speed; and

  *V* = the mean wind speed.

- **Wind power density (WPD) -** is a truer indication of a site's wind energy potential than wind speed alone. Its value combines the effect of a site's wind speed distribution and its dependence on air density and wind speed. WPD is defined as the wind power available per unit area swept by the turbine blades and is given by the following equation:

$$WPD = \frac{1}{2n}\sum_{i=1}^{n}(\rho)\left(v_i^{\,3}\right)\ (\mathrm{W/m^2})$$

n = the number of records in the averaging interval;

ρ = the air density (kg/m³); and

$v_i^3$ = the cube of the with wind speed (m/s)

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[53] Wind Resource Assessment Handbook - Fundamentals for Conducting a Successful Monitoring Program, NREL, 1997

The air density term in the WPD must be calculated. It depends on temperature and pressure (thus altitude) and can vary 10% to 15% seasonally. If the site pressure is known (e.g., measured as an optional parameter), the hourly air density values with respect to air temperature can be calculated from the following equation:

$$\rho = \frac{P}{RT} \quad (\mathrm{kg/m^3})$$

Where:
*P* = the air pressure (Pa or N/m²);
*R* = the specific gas constant for air (287 J/kg·K);
*T* = the air temperature in degrees Kelvin (°C+273).

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

$$\rho = \left(\frac{P_o}{\mathrm{RT}}\right) \exp^{\left(\frac{-g \cdot z}{\mathrm{RT}}\right)} \quad (\mathrm{kg/m^3})$$

Where:

Po = the standard sea level atmospheric pressure (101,325 Pa), or the actual sea level; adjusted pressure reading from local airport:

g = the gravitational constant (9.8 m/s²); and

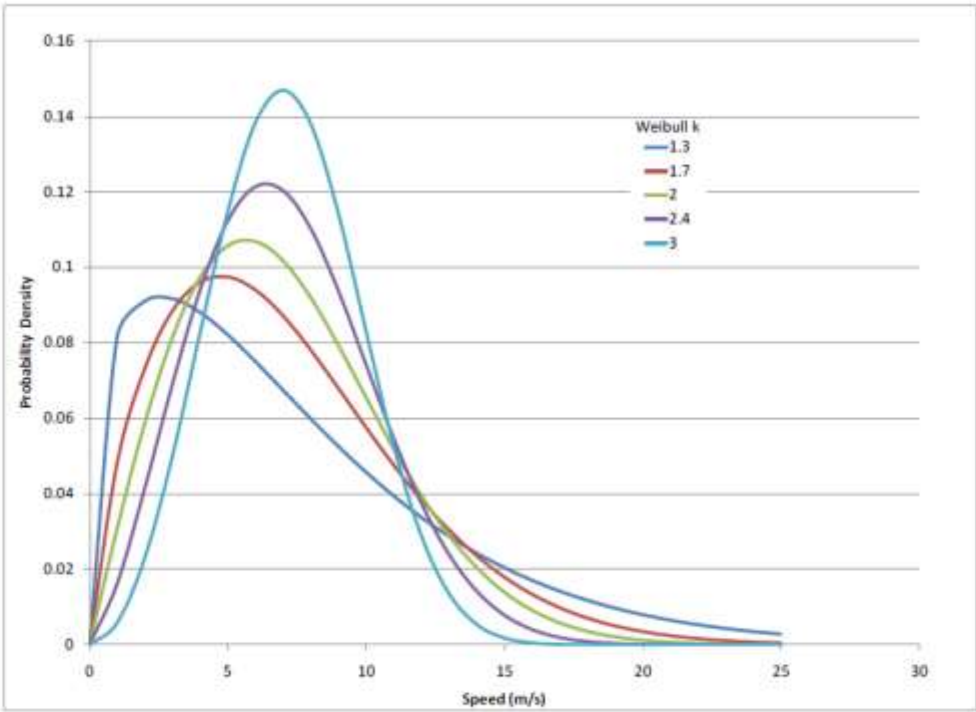
z = the site elevation above sea level (m).

- **Speed Frequency Distribution and Weibull Parameters** – the speed frequency distribution is a critical piece as it is used directly in estimating the power output of a wind turbine. The frequency distribution represents the number of times in the period of record that the observed speed falls within particular ranges, or bins. The speed bins are typically 0.5 m/s or 1 m/s wide and span at least the range of speeds defined for the turbine power curve, i.e., from 0 m/s to 25 m/s and above. It is usually presented in reports as a bar chart, or histogram, covering all directions.
  The Weibull distribution is a mathematical function that is often used to represent approximately the wind speed frequency distribution at a site. In the Weibull distribution, the probability density (the probability that the speed will fall in a bin of unit width centred on speed v) is given by the equation:

$$p(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} e^{-\left(\frac{v}{A}\right)^k}$$

A – Scale parameter related closely to mean speed

K – Shape parameter, width of distribution range from 1 to 3.5, the higher values indicating a narrower frequency distribution




Weibull probability density curves for a range of values of k. All curves have the same A: 8.0 m/s.

Figure 13 Weibull probability density curves [54]

- **Wind Rose** – to show the information about the distributions of wind speeds, and the frequency of the varying wind directions. In most projects, the spacing between turbines along the principle wind direction is much greater than the spacing perpendicular to it. This configuration maximizes the density of wind turbines while keeping wake interference between the turbines, and hence energy losses, manageable. A wind rose gives you information on the relative wind speeds in different directions, i.e. each of the three sets of data (frequency, mean wind speed, and mean cube of wind speed) has been multiplied by a number which ensures that the largest wedge in the set exactly matches the radius of the outermost circle in the diagram. 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:

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

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

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

*Ni* = the number of records in direction sector *i*,

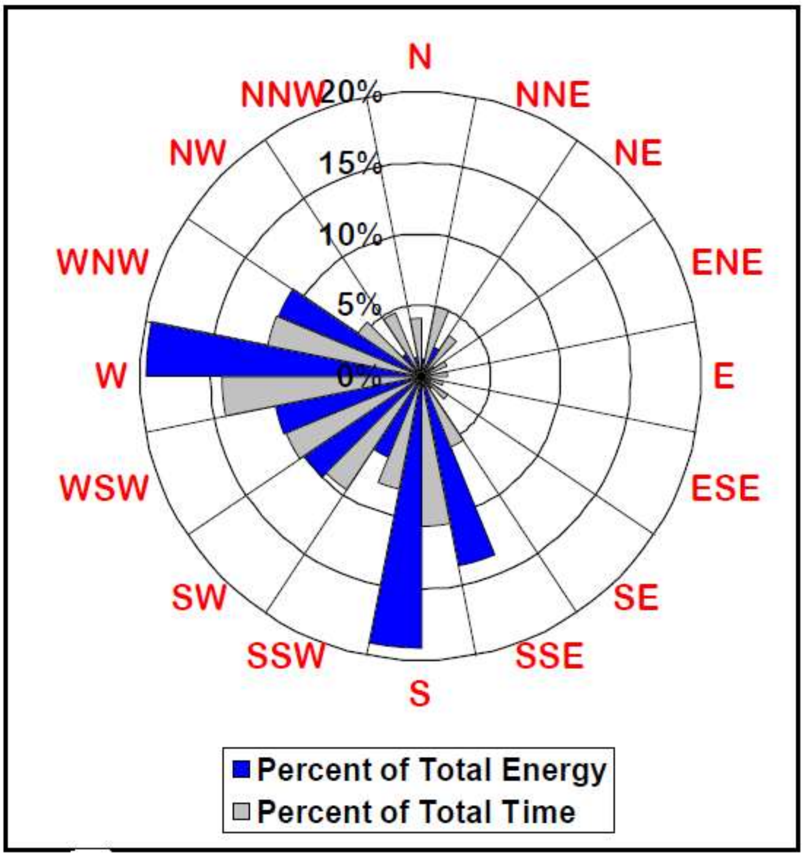
*N* = the total number of records in the data set,

[54] Wind Resource Assessment Handbook, NUSERDA, 2010

*vj* = the wind speed for record *j*,

*WPDi* = the average wind power density for direction sector *i*,

*WPD* = the average wind power density for all records




Wind rose plot example.

Figure 14 – wind rose plot example [55]

- **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 influence rests 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 speed up, producing an upsurge in the observed speed. Provisionally on the boom length and tower geometry, these effects can be up to several %, a substantial bearing on a resource assessment, particularly if the wind comes often from a narrow range of directions. By modifying for these tower influences, a more precise free-stream speed interpretation can be attained for an individual sensor. At present, there are no commercial tools available, so custom tools must be developed

[55] Wind Resource Assessment Handbook, NUSERDA, 2010

by the resource analyst using information available in the literature. An alternative is averaging valid data from two sensors at the same height and orienting the recommended angular distance apart (depending on tower type). This often mitigates or virtually eliminates tower effects in the combined data record.[56]

- **Inclined flow** - cup anemometers, are sensitive to variable degrees of off-horizontal winds depending on the geometry of the cups and instrument. Research has recognised the influence of flow angle on wind speeds recorded by cup anemometers but interpreting of this information needs knowledge of the flow angle at the tower. This can be attained from a sodar, a lidar, or a vertical anemometer mounted on the tower.

**Data substitution and averaging**

The data validation process up until now has pursued to keep valid data from each sensor intact and separate from data from other sensors. There are two methods of combining the data from different sensors: substitution and averaging.

- **Data substitution** - aims to create the longest possible data record by filling gaps in one sensor's record with data from one or more other sensors. For anemometers, the substituted data ideally should come from an instrument at the same height. It is generally straightforward to fill gaps in the directional data record using valid data from another vane. The analyst should merely check to make sure that there is no significant, persistent bias between the two vanes' directional readings during periods when both produce valid data.
- **Data averaging** - seeks to reduce the uncertainty in the observed speeds by averaging data from two different anemometers at the same height. Averaging can be used only when the data from both sensors are valid.

[56] Wind Resource Assessment Handbook, NUSERDA, 2010

# Comparison of observed wind data with historical norm

The last stage in characterizing the wind resource, before extrapolating the data to hub location is to adjust the observed wind climate to the historical norm. Average wind speeds can fluctuate considerably from the norm even over periods of a year. For example, the uncertainty in the long-term mean wind speed, based on a year of measurement, is normally about 3-5% corresponding to perhaps 5-10% in the mean wind plant production. This would be a substantial influence when weighing the risk of financing a wind project. Reducing this vagueness is the primary goal of the climate-adjustment process.

The principal technique for executing climate adjustments is called MCP, which stands for measure, correlate, predict. The wind resource is measured at a site, over a period ranging from several months to several years. The observed winds are then correlated with those recorded at a long-term reference, such as an airport weather station, and a relationship between them is established. Then, the much longer historical record from the reference is applied to this relationship to predict the long-term mean wind resource at the target site.

## Requirements for accurate MCP

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

- The site and reference station must be in a considerably similar wind climate. This means that variations in wind speed at each location should be well correlated in time. The correlation can be measured qualitatively by plotting a time series of observed wind speeds for both the target and reference stations. A quantitative measure such as the Pearson correlation coefficient (r) can also be used. The square of the correlation coefficient, r2, can be thought of as the fraction of the variation in the values of one variable that can be explained by a linear equation with another variable.
- The site and reference station must have a homogenous wind speed record. A wind speed record is said to be homogeneous if the measurements have been taken continuously at the same location and height with equivalent instrumentation. In the case of the reference station, its record should be substantially longer than, and overlap with, that of the target site.

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

**Correlation** [57]

If a wind project site is in flat, open terrain, it is frequently easy to locate a weather station in the locality that has similar wind climate. However, if the project site in on a bare ridge or mountain top, and the nearest reference stations are in shielded valleys; or the project site may be near a coastline while the available reference stations are well inland. The result then can be comparatively poor correlations between the site and reference station. The feebler the correlation with the reference station, the bigger the doubt in the attuned long-term wind resource at the target site.

Presuming normally distributed annual wind speed fluctuations and a consistent reference station data record, the following simple equation approximates the overall uncertainty in the long-term mean wind speed as a function of the correlation coefficient, $r^2$

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

*σA* = the standard deviation of the annual mean wind speed as a % of the mean

*NR* = the number of years of reference data

*NT* is the number of years of concurrent reference and target data

It is key to decide what averaging interval should be applied to the wind speeds when using the MCP process. The best averaging interval for MCP is related to the time scale at which wind variations may be experienced concurrently by the reference and target sites. If the interval is too short, then a large amount of the speed variations may not contain any useful information about the relationship. If the interval is too long, on the other hand, then important information about the relationship may be lost. Consecutively, the ideal time interval is related to the size of typical weather disturbances and their rates of motion. The interval of a wind "event" (gust occurring in a matter of seconds or a sustained period of high winds lasting several days) - equals the size of the related weather disturbance divided by its speed relative to the observer. A wind fluctuation cannot take place concurrently at two points unless both are within the realm of influence of the same disturbance. Thus, the shortest time scale over which correlated variations can occur, Δ*t*, is the distance between the target and reference stations, *D*, divided by typical or average background wind speed.

$$\Delta t \approx \frac{D\ (m)}{v\left(\frac{m}{s}\right)}\ (s)$$

Δ*t* = time scale over which correlated variations occur

[57] Wind Resource Assessment Handbook, NUSERDA, 2010

$D$ = the distance between the target and reference stations

$V$ = typical or average background wind speed

As an overall standard, when the reference is a regular surface weather station located some distance away from the target tower, daily averaging serves well. This has the advantage in that it is simple to apply and it decreases the effect of dissimilarities in 24-hour wind speed patterns related to tower height and station location. The only time a shorter interval such as one hour or 10 minutes might realistically be used is when the reference station is within a few km of the target site. This occurs most often when secondary masts are correlated with a primary reference tower within the project area.

**Homogenous wind speed observations**[58]

The prerequisite for an extended, homogeneous reference data record can also be problematic as measurement standards change from time to time as national weather agencies seek to improve their measurement technology and data products. Towers are moved or heights are changed, manual recording replaced with automated digital equipment, resulting is large discontinuity of recorder wind speeds. In some cases, this incremental data ambiguity will result in a total MCP uncertainty that is higher than if the on-site data were used alone; thus it is better not to use it at all. Another challenge is fluctuating site conditions around reference stations, which can generate false trends in wind speeds. In the absence of substantial trend and discontinuities, the improbability in the long-term mean wind speed derived through MCP should decrease as the length of the reference station's record increases; but only to the extent that the two stations are correlated in time.

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

$$\boldsymbol{\varepsilon} \approx -\frac{\boldsymbol{N}}{\mathbf{2}}\boldsymbol{s}\ (\%)$$

$s$ = the trend slope in percent per year

$N$ = the number of years in the reference data record

Hence, where incorrect trends are existing, the extent of the potential bias increases with the length of the reference period. The problem is compounded if the trend is caused by a

58 Ibid 57

real and persistent change in climate because then the bias resulting from the ordinary MCP process may be even larger, if the trend continues in the future.

MCP – is still a pillar of wind resource assessment but must be applied with substantial caution. The following practical guidelines are offered:

- A comprehensive exploration of potential reference stations and data sources is required. The more data sets accessible for analysis, the easier it is to discover in homogeneities.
- The data recovery rate at the reference stations should be high and constant over time, as long gaps/substantial changes will render the data homogeneity suspect.
- The available documentation for each station should be inspected carefully to determine whether its instruments, tower height, location, or measurement protocols have changed. The reference period should be the most recent period for which conditions at the station have remained substantially the same.
- The reference data for each station should be assessed visually and statistical tests applied where appropriate, to detect trends or in homogeneities larger than can easily be explained by normal fluctuations.
- Be cautious of reference data records extending back more than 15 years, even if there has been no documented change in the station equipment or protocols. There is little assurance that measurements are characteristic of the more recent local wind climate.

# Wind flow modelling

Wind flow modelling assesses the wind resource at every proposed wind turbine location so that the wind plant's overall production can be calculated and its design can be optimized. This entails extrapolating the wind resource measured using a numerical wind flow. Wind flow modelling must account for each turbine's influence on the operation of other turbines - the so-called wake effect. There will be a wake behind the turbine, i.e. a long trail of wind which is quite turbulent and slowed down, when compared to the wind arriving in front of the turbine. Wake modelling is typically performed separately from wind flow modelling using specialized software.

There are too many methods with very diverse characteristics to propose one best option. Thus, an overview of the different modelling approaches that are available, including their strengths and weaknesses, and establish some general guidelines applicable to all methods where, most importantly, the appropriate use of measurements to manage and limit errors.

## Types of wind flow models

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

### Conceptual models

Conceptual models are theories defining how the wind resource is expected to fluctuate across the terrain, based on a combination of practical experience and a theoretical understanding of boundary layer meteorology.

A simple theoretical model might predict that the wind resource at one location (a turbine) is the same as that measured at a different location (a met mast). This could be a good model in comparatively flat terrain or along a fairly uniform ridgeline, for example. Where the terrain and land cover differ significantly, more detailed predictions are needed. This will including models for the influence of elevation on the mean wind speed, the relationship between upwind and downwind slope and topographic acceleration, channelling through a mountain gap, and the impact of trees and other vegetation. These theories are then converted into practical recommendations for the placement of wind turbines, accompanied by estimates of the wind resource they are likely to be subject to.

As wind projects become larger and are built in more mixed wind climates and sites, it becomes more and more difficult to employ a solely conceptual approach in a precise or repeatable way. Nevertheless, a good conceptual understanding of the wind resource is a valuable asset in all spatial modelling. Most important, it offers a check on the sensibleness of other methods. A good conceptual understanding is better than a bad numerical model, or a good numerical model that is wrongly employed.

**Experimental models**

Experimental approaches indicate the creation of a sculpted scale model of a wind project area and testing it in a wind tunnel. The environments in the wind tunnel, such as the speed and turbulence, must be corresponding to the scale of the model to imitate real conditions as closely as possible. While the wind tunnel is running, the wind speeds are measured at numerous points on the scale model using miniature anemometers. The outcomes form a depiction of how the wind fluctuates across the site. The relative speeds between points are then usually linked to a mast where the speeds have been measured in the field. It may even provide exclusive insights in areas where numerical wind flow models are prone to break down, such as near the edge of a steep cliff. Still, few implement this technique because of the time and special skills required to build the model and the need for access to a wind tunnel. In addition, the method has some limitations for correctly pairing atmospheric parameters to the physical scale.

**Statistical models**

Statistical models are based on relationship derivatives from on-site wind measurements. Typically one tests different predictive parameters - such as elevation, slope, exposure, surface roughness, and other indicators - to find those that seem to have the strongest connection with the observed wind resource at several masts. Theoretically, any parameters can be used, although in reality focus is on those for which there is a reasonable theoretical basis that a relationship might be present. This is one model where a good conceptual understanding is advantageous.

Suppose one has assessed the mean wind speeds at numerous different towers at different points within a wind resource area. Suppose the speeds are plotted against slope for example, and a strong correlation is found. From this relationship a linear equation ($y = mx + b$) could be obtained and applied to predict the speed at any other point in the area.

Statistical models are appealing because they are substantiated in measurement and are fairly simple and transparent - unlike numerical wind flow models. One of the possible limitations of statistical methods is that they can generate big errors when making predictions outside the range of conditions used to train the model. In this respect, statistical models can be less reliable than numerical wind flow models, which are designed to produce credible results in a wide range of conditions. Defining the accuracy of a statistical model is a challenge as it calls for division of the dataset into two groups: one to train the model, the other to validate the model. Nevertheless, statistical models are a valid approach when proper procedures are followed and can be combined with other approaches, such as numerical wind flow models.

**Numerical wind models**

The most popular methods of spatial modelling count on numerical wind flow models. There are several wind flow models in use by the wind industry today, which are based on a variety of theoretical approaches. All try to resolve some of the physical equations governing motions of the atmosphere, with varying degrees of complexity.

- **Mass-consistent models** – are the first generation of wind flow models developed in the 1970s and 1980s (e.g., NOABL35, MINERVE). They solve just one of the physical equations of motion governing mass conservation. When applied to the atmosphere, the principle of mass conservation implies that wind forced over higher terrain must accelerate so that the same volume of air passes through the region in a given time. As a result, these models predict stronger winds on hill and ridge tops and weaker winds in valleys. They don't look at thermally-driven wind patterns, such as sea breezes and mountain-valley circulations, and flow separations on the lee side of hills or mountains. The answer obtainable by a mass-conserving model is not unique: the governing equation essentially allows for a countless variety of solutions. Most models are designed to depart by the smallest amount from an initial wind field "guess" derived from observations. Such a characteristic sets this type of model apart from other numerical models, which make no such assumption. It also means that mass-consistent models are able to take advantage of data from supplementary meteorological towers in a natural way, by modifying the initial guess.
- **Jackson-Hunt Models –** are the next generation of models (e.g., WAsP, MS-Micro MS3DJH,Raptor, Raptor NL) and were originally developed in the 1980s and 1990s based on a theory advanced by Jackson and Hunt. The model solves the linearized Navier–Stokes equations under several assumptions: steady-state flow, linear advection and first-order turbulence closure. In addition, the terrain is only taken into account as a first-order perturbation. The key simplification in the Jackson-Hunt theory is that the terrain triggers a small distress to an otherwise constant background wind. This assumption allows the equations to be solved using a very fast numerical technique.
  - The Wind Atlas Analysis and Application Program (WAsP) developed at Risø DTU National Laboratory is a spectral model based on the Jackson–Hunt theory. The necessary inputs to WAsP include the terrain elevation and surface roughness as well as the measured mean wind speeds and frequencies by direction sectors from onsite meteorological masts. Like most diagnostic microscale models, WAsP calculates the mean wind flow for each directional sector independently. The WAsP model ignores effects of thermal

stability and temperature gradients. Thermal stratification and buoyancy forces can have a large influence on the response of wind to terrain.

**CFD models**

The difference between CFD and Jackson-Hunt models is that CFD models solve a more complete form of the equations of motion known as the Reynolds-averaged Navier-Stokes, or RANS, equations. They do not assume the terrain induces a small perturbation on a constant wind field. This means they are competent of mimicking non-linear responses of the wind to steep terrain, such as flow separation and recirculation. They also do not have to make certain other simplifying assumptions, such as that shear stress and turbulence act only near the surface. This, in turn, allows CFD models to simulate the influences of roughness changes and obstacles directly. They provide useful information concerning turbulence intensities, shear, direction shifts, and other features of wind flow in complex terrain.

Limitations of CFD models have been attributed to various factors, including inaccuracies in initial and boundary conditions (usually assumed to be homogeneous and follow a neutrally stratified, logarithmic profile), limited grid resolution, and treatment of turbulence. The added complexity of the models may be a problem as some users may not be well equipped to run them properly. Another factor is that CFD models are not designed to take into account any circulations due to temperature gradients. The lack of a complete prognostic equation for temperature in CFD models is, in turn, the result of another assumption made in most CFD models, which is that the wind flow is steady-state and there is a constant incoming wind.

**Mesoscale numerical weather prediction (NWP) models**

This type of model has been developed first for weather forecasting and similarly to CFD models, NWP models solve the Navier-Stokes equations. Dissimilar to CFD models, they include parameterization schemes for solar and infrared radiation, cloud microphysics and convection (cumulus clouds), a soil model, and more. Thus, they integrate the dimensions of both energy and time, and are adept in replicating sea breezes and atmospheric stability, or buoyancy. The wind is never in equilibrium with the terrain because of the constant flow of energy into and out of the region, through solar radiation, radiative cooling, evaporation and precipitation, the cascade of turbulent kinetic energy down to the smallest scales and dissipation into heat - even sound waves.

Mesoscale models offer accurate simulations of wind flows in complex terrain, but they require enormous computing power to run at the scales required for the assessment of wind projects. One way around this problem is to couple mesoscale models with a microscale model of some kind. This could be a statistical model, if there is sufficient on-site wind data to create reliable statistical relationships. More often, it is a simplified wind flow model - usually either a mass-consistent model or a Jackson-Hunt model.

# Global tools and data sources availiable online to make preliminary resource potential assessments

## Global data resources

- **Global wind atlas** - https://globalwindatlas.info/

The Global Wind Atlas is a free, web-based application developed to help investors identify potential high-wind areas for wind power generation virtually anywhere in the world, and perform preliminary calculations. It provides freely downloadable datasets based on the latest input data and modelling methodologies. Users can additionally download high-resolution maps showing global, regional, and country wind resource potential. It also provides:

- Wind resource data accounting for high-resolution effects.
- Uses microscale modelling to capture small-scale wind speed variability (crucial for better estimates of total wind resource).
- Uses a unified methodology over the entire globe and update the Global Wind Atlas as methodologies develop.
- Ensures transparency about the methodology used.
- Supports the verification of the results in the long-term by coupling to measurement data and campaigns.

**Limitations of the Global Wind Atlas**

- Mesoscale modelling - uncertainties associated with the mesoscale modelling include: representativeness of the large scale forcing and sampling, model grid size, description of the surface characteristics, model spin-up, simulation time and modelling domain size.
- Microscale modelling - uncertainties associated with the microscale modelling include the orographic flow model within WAsP, the surface description and departures from the reference wind profile. Concerning the orographic flow model, the model performs well when the surrounding terrain is sufficiently gentle and smooth to ensure mostly

attached flows. With the global coverage of the GWA, they use the BZ-model in areas beyond its recommended operational envelope.

- **Renewable Ninja**
  https://www.renewables.ninja/

  Run simulations of hourly power output from wind farms by clicking anywhere on the map, choosing your technology from the side menu, and hitting "Run". You can also download ready-made datasets by clicking "Country" on the sidebar.

- **WAsP** (**Wind resource assessment, siting & energy yield calculations)**

  http://www.wasp.dk/wasp

  WAsP is the industry-standard PC software for wind resource assessment. WAsP is used for sites located in all kinds of terrain all over the world and includes models and tools for every step in the process from wind data analysis to calculation of energy yield for a wind farm.

- **EARTHDATA**

  https://earthdata.nasa.gov/

  The Earth Observing System Data and Information System (EOSDIS) is a key core capability in NASA's Earth Science Data Systems (ESDS) Program. It provides end-to-end capabilities for managing NASA's Earth science data from various sources – satellites, aircraft, field measurements, and various other programs.

- **Corine Land Cover 2006**

  http://maps.eea.europa.eu/EEAGalleryBasicviewer/v1/?appid=f9b34d047a154184805687707eb7dfe5&group=9a0c196cb389491ea114eaca9fb07b5e

  CORINE Land Cover (CLC) is a geographic land cover/land use database encompassing most of the countries of Europe.

Protected Areas

- **Protected planet** – https://www.protectedplanet.net/
- Protected Planet is the most up to date and complete source of information on protected areas, updated monthly with submissions from governments, non-governmental organizations, landowners and communities.
- **EUNIS** - https://eunis.eea.europa.eu/index.jsp

The European nature information system, EUNIS, brings together European data from several databases and organisations into three interlinked modules on sites, species and habitat types.

## Calculators for different parameters

- **Wind speed extrapolation**

https://websites.pmc.ucsc.edu/~jnoble/wind/extrap/

- **Roughness calculator**

http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/stat/unitsw.htm#roughness

- **Wind speed calculator**

http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/calculat.htm

- **Weibull Distribution Plotter Programme**

http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/weibull/index.htm

- **Wind Rose Plotter Programme**

http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/roseplot.htm

- **Wind Shade Calculator**

http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/shelter/index.htm

- **Wind Turbine Power Calculator**

http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/pow/index.htm

- **Wind Turbine Efficiency & Comparison Calculator**

http://perso.bertrand-blanc.com/Resume/Experience/Energy/index.html

- **Wind Turbine Generator Equation Calculator**

https://www.ajdesigner.com/phpwindpower/wind_generator_power.php

Northern Periphery and Arctic Programme 2014-2020

EUROPEAN UNION
Investing in your future
European Regional Development Fund

# GREBE

Generating Renewable Energy Business Enterprise

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GREBEProject

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## Project Partners

GREBE will be operated by eight partner organisations across six regions:

- WDC
- Action Renewables – the future of energy, today
- Luke – Natural Resources Institute Finland
- Forskningsparken i Narvik
- eri
- Fermanagh & Omagh District Council – Comhairle Ceantair Fhear Manach agus na hÓmaí
- Innovation Center Iceland
- Karelia

## About GREBE

GREBE is a €1.77m, 3-year (2015-2018) transnational project to support the renewable energy sector. It is co-funded by the EU's Northern Periphery & Arctic (NPA) Programme. It will focus on the challenges of peripheral and arctic regions as places for doing business, and help develop renewable energy business opportunities provided by extreme conditions.