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INTRODUCTION

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

Wind resource assessment is the process of estimating how much fuel will be available for a wind power plant over the course of its useful life. This process is the single most important step for determining how much energy the plant will produce, and ultimately how much money it will earn for its owners. For a wind project to be successful, accurate wind resource assessment is therefore essential.

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

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

Wind Resource Assessment: A Practical Guide to Developing a Wind Project, First Edition.
Michael Brower et al.

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

1.1 WHERE DO WINDS COME FROM?

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

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

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

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

A similar circulation pattern known as a *polar cell* is set up between high latitudes and the poles. Lying between the polar and Hadley cells are the midlatitude (Ferrel) cells, which circulate in the opposite direction. Unlike the others, they are not driven by convection but rather by the action of sinking and rising air from the adjacent cells. Once again the Coriolis effect asserts itself as the air flowing poleward along

[1]The Coriolis effect is a property of observing motions from a rotating reference frame—in this case, the earth. The earth's surface moves faster around the axis at the equator than it does closer to the poles. If an object moves freely toward the equator, the surface beneath it speeds up toward the east. From the perspective of an observer on the surface, the object appears to turn toward the west.

[2]By convention, wind direction is denoted by the direction the wind comes *from*. If the air is moving toward the north, it is said to be a southerly wind.

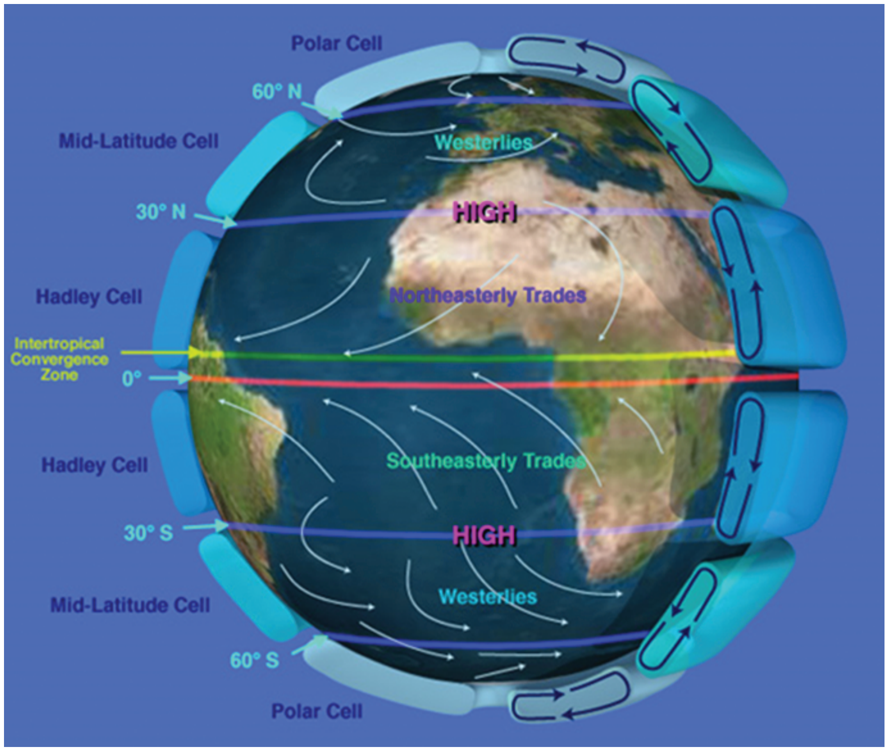

Figure 1-1. The main global atmospheric circulations. *Source:* NASA/JPL-Caltech.

the surface turns east, creating the westerlies. The westerlies are the reason wind resources tend to be so good in the temperate and high latitudes (around 35–65 °N) of North America, Europe, and Asia, as well as the southern extremes of Africa, South America, and Australia.

Superimposed on these global circulation patterns are many regional patterns. Large land masses heat up and cool down more rapidly than the oceans, and even within land masses, there are variations in surface heating, for instance, between a snow-covered mountain top and a green valley below or between a desert and a cultivated plain. The resulting temperature gradients set up what are called *mesoscale atmospheric circulations*—mesoscale because they are in between the global scale and the local scale, or microscale.

The most familiar mesoscale circulation is the sea breeze. During a typical summer day, the land becomes warmer than the ocean, the pressure drops as the air above it expands and rises, and relatively cool, dense air is pulled in from the ocean. At night, the process reverses, resulting in a land breeze. Normally, sea breezes are weak, but where the wind is concentrated by terrain, they can have a powerful effect. This is the primary mechanism behind the very strong winds found in coastal mountain passes in the US states of California, Oregon, and Washington, and in comparable passes in other countries.

While temperature and pressure differences create the wind, it can be strongly influenced by topography and land surface conditions as well, as the example of coastal mountain passes attests. Where the wind is driven over a rise in the terrain, and especially over a ridge that lies transverse to the flow, there can be a significant acceleration, as the air mass is "squeezed" through a more restricted vertical space. Thanks to this effect, many of the best wind sites in the world are on elevated hilltops, ridges, mesas, and other terrain features. However, where the air near the surface tends to be cooler and heavier than the air it is displacing, as in the sea breeze example, it has a tendency to find paths around the high ground rather than over it. In such situations, it is often the mountain passes rather than the mountain tops that have the best wind resource.

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

1.2 KEY CHARACTERISTICS OF THE WIND

The annual average wind speed is often mentioned as a way to rate or rank wind project sites, and indeed, it can be a convenient metric. These days, most wind project development takes place at sites with a mean wind speed at the hub height of the turbine of 6.5 m/s or greater, although in regions with relatively high prices of competing power or other favorable market conditions, sites with a lower wind resource may be viable. However, the mean speed is only a rough measure of the wind resource. To provide the basis for an accurate estimate of energy production, the wind resource must also be characterized by the variations in speed and direction, as well as air density, in time and space.

1.2.1 The Temporal Dimension

The very short timescales of seconds and less is the domain of turbulence, the general term for rapid fluctuations in wind speed and direction caused by passing pressure disturbances, or eddies, which we typically experience as brief wind gusts and lulls. Turbulence is a critical mechanism by which the atmosphere gradually sheds the energy built up by solar radiation. Unfortunately, it has little positive role in power production because wind turbines cannot respond fast enough to the speed variations. In fact, high turbulence can cause a decrease in power output as the turbine finds itself with the wrong pitch setting or not pointing directly into the wind. In addition, turbulence contributes to wear in mechanical components such as pitch actuators and yaw motors. For this reason, manufacturers may not warrant their turbines at sites where the turbulence exceeds the design range. Knowledge of turbulence at a site is thus very important for resource assessment.

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

On a timescale of 12–24 h, we see variations associated with the daily pattern of solar heating and radiative cooling of the earth's surface. Depending on the height above ground and the nature of the wind climate, wind speeds at a given location typically peak either at midafternoon or at night. Which pattern predominates can have a significant impact on plant revenues in markets that price power according to the demand or time of day. For example, regions in which air-conditioning loads are important often see a peak in power demand in the afternoon, and regions in which there is heavy use of electricity for home heating may experience a peak in the early evening.

The influence of the seasons begins at timescales of months. In most midlatitude regions, the better winds usually occur from late fall to spring, while the summer is less windy. Sites experiencing strong warm-weather mesoscale circulations, such as the coastal mountain passes mentioned earlier, are often an exception to this rule, and winds there tend to be strongest from late spring to early fall. Because of seasonal variations like this, it is difficult to get an accurate fix on the mean wind resource with a measurement campaign spanning much less than a full year. Furthermore, as with diurnal variations, seasonal variations can impact plant revenues. Power prices are usually the highest in summer on a summer-peaking system and in winter on a winter-peaking system.

At annual and longer timescales, we enter the domain of regional, hemispheric, and global climate oscillations, such as the famous El Niño. These oscillations, as well as chaotic processes, account for much of the variability in wind climate from year to year. They are the main reason why it is usually desirable to correct wind measurements taken at a site to the long-term historical norm.

1.2.2 The Spatial Dimension

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

The spatial scales of interest are related to the size of wind turbines and the dimensions of wind power projects. The rotors of modern, large wind turbines range in diameter from 70 to 120 m. Wind turbines are typically spaced some 200–800 m apart, and large wind projects can span a region as wide as 10–30 km. Within this overall range, a detailed map of the variations is essential for the optimal placement of wind turbines and accurate estimates of their energy production.

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

1.2.3 Other Characteristics of the Wind Resource

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

Knowledge of the frequency distribution of wind directions is key for optimizing the layout of wind turbines. To reduce wake interference between them (described below), turbines are generally spaced farther apart along the predominant wind directions than along other directions.

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

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

1.3 WIND POWER PLANTS

Conceptually, a wind turbine is a simple machine (Fig. 1-2). The motion of the air is converted by the blades (lifting airfoils very similar to airplane wings) to torque on a shaft. The torque turns a power generator, and the power flows to the grid.

However, this simple picture disguises many subtle design features. The typical modern large wind turbine is an immense, complicated machine ranging from

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

65 to 100 m in height at the hub, with a rotor 70–120 m in diameter, and with a rated capacity of 1–5 MW. The turbine must operate reliably and at peak efficiency under a wide range of wind conditions. This requires numerous components, from nacelle anemometers to pitch actuators and yaw drives to power electronics, working together in an integrated system.

Perhaps, the key characteristic of a wind turbine from the perspective of wind resource assessment is the turbine power curve (Fig. 1-3). This describes the power output as a function of wind speed measured at the hub. It is characterized by a cut-in speed, typically around 3 or 4 m/s, where the turbine begins turning and generating power; a sloping portion, where the output increases rapidly with speed; a rated speed, typically around 13–15 m/s, where the turbine reaches its rated capacity; and a cut-out speed, above which the turbine control software shuts the turbine down for its protection.

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

Wind power plants are likewise conceptually simple: they are just arrays of wind turbines linked through a power collection system to the power grid (Fig. 1-4). However, designing a wind project often entails delicate trade-offs between, for example, total plant output and construction cost.

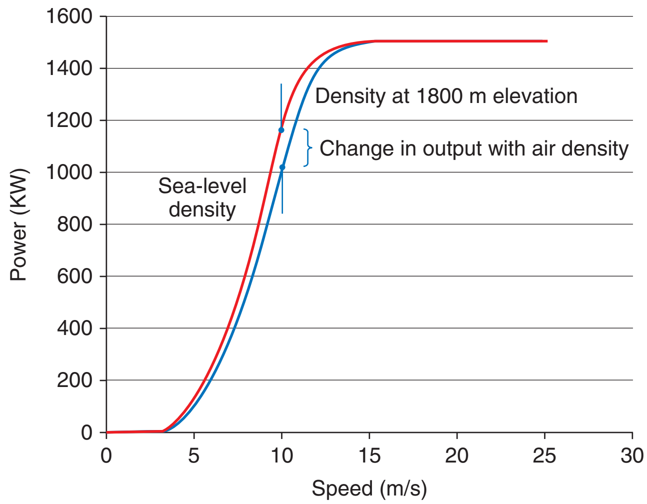

Figure 1-3. Typical power curve for a 1.5-MW turbine at two different air densities. *Source:* AWS Truepower.

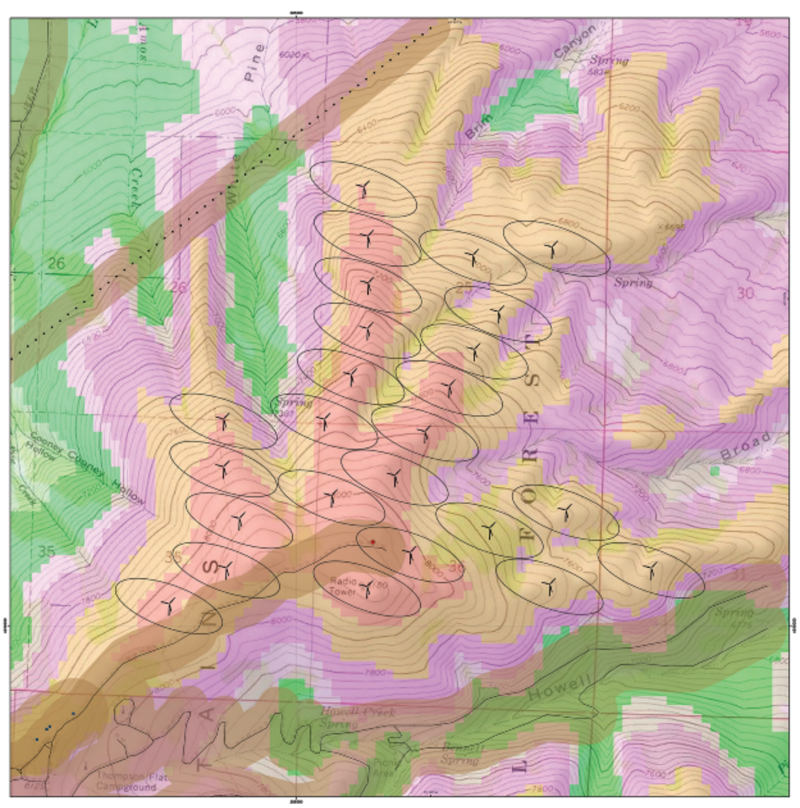

Figure 1-4. Layout of a proposed wind farm. *Source:* AWS Truepower.

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

The process begins by producing a detailed picture of how the wind resource is distributed across the site, supported by measurements and spatial modeling of some kind. In sites with complex terrain and wide variations in land cover, this can be a significant technical challenge. A further complication is wake (or array) interference between turbines. When a turbine extracts energy from the wind, a zone of reduced wind speed and increased turbulence is created behind it (Fig. 1-5). Any turbines that happen to be within this wake will generally produce less power than if the upwind turbines were not there. Fortunately, wakes tend to expand and dissipate with distance downwind as turbulence exchanges energy with the surrounding, undisturbed wind flow. How the wakes from all the turbines impact plant production is usually estimated with a specialized wake model.

1.4 PURPOSE AND ORGANIZATION OF THIS BOOK

As we have seen, designing a wind project and estimating its energy production depend on a detailed and accurate assessment of the wind resource, which is where this book comes in. The book is primarily intended to give guidance to practitioners and students on the accepted methods of wind resource assessment for utility-scale wind farms. The goal is not to impose conformity in every respect. On the contrary, the book often highlights areas where there is room for reasonable variation, even disagreement, on the approaches that can be used. Nonetheless, the range of variation has limits. It may be acceptable in some cases to install a tower with just two levels of anemometers, rarely just one. It may be fine to use a new or unusual atmospheric model, but not without anchoring the results in reliable measurements or testing the model's accuracy. What we hope the reader gains from this book is a clear understanding of those limits.

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

The book is organized in the order of the main stages of wind resource assessment. The first several chapters focus on the nuts and bolts of conducting a wind measurement campaign. It starts with an overview of the wind resource assessment process. Then it moves through site selection, measurement parameters and tower instrumentation, tower installation and maintenance, and data collection and handling. The last chapter in this group, Chapter 8, focuses on remote sensing (lidar and sodar).

The next section of chapters addresses how the wind resource data are analyzed. It starts with quality control (QC) and validation and then moves on to characterizing the observed wind resource. Subsequent chapters cover extrapolating the resource estimates to hub height, correcting short-term measurements to long-term historical conditions, and wind flow modeling. Chapter 14 is devoted to special issues concerning offshore sites. Chapter 15 discusses uncertainty in wind resource estimates, including the different categories of uncertainty and their typical values. The last chapter, Chapter 16, provides an overview of the steps involved in designing a wind project and estimating its long-term average energy production.

In most chapters, discussion questions aimed at classroom use and recommendations for further reading are provided.

1.5 QUESTIONS FOR DISCUSSION

1. What is the principal cause of pressure gradients (differences) between different points on the earth's surface? When a pressure gradient increases, how does the wind tend to change?
2. What are the three principal mechanisms affecting the speed and direction of the wind near the earth's surface?
3. Give two examples of mesoscale atmospheric circulations. Does either of these mechanisms occur in the country or region where you live? If so, where?
4. What would have a larger surface roughness length, a grass field or a forest? All other things being equal, how is this difference likely to affect wind speeds at the height of a wind turbine?

5. What is turbulence, and on what timescales does it occur? How does turbulence affect wind turbine output?
6. What is wind shear, and why is it important?
7. What parameters of the wind resource need to be known to estimate the energy production of a single turbine? Why is it important to know the predominant wind direction when designing a wind power plant with more than one turbine?
8. How is air density related to the amount of energy that can be generated from the wind?

SUGGESTIONS FOR FURTHER READING

Ahrens CD. Essentials of meteorology. 5th edn. USA: Brooks Cole; 2007. p. 504.

Brock FV, Richardson SJ. Meteorological measurement systems. USA: Oxford University Press; 2001. p. 304.

Burton T, Sharpe D, Jenkins N, Bossanyi E. Wind energy handbook. New York: John Wiley & Sons, Inc.; 2001. p. 642.

Garratt JR. The atmospheric boundary layer. New York: Cambridge University Press; 1992. p. 336.

Lutgens FK, Tarbuck EJ, Tasa D. The atmosphere: an introduction to meteorology. 11th edn. USA: Prentice Hall; 2009. p. 508.

Robinson P, Henderson-Sellers A. Contemporary climatology. 2nd edn. USA: Prentice Hall; 1999. p. 352.

Stull RB. Meteorology for scientists and engineers. 2nd edn. USA: Brooks Cole; 1999. p. 528.

Wallace JM, Hobbs PV. Atmospheric science: an introductory survey. 2nd edn. USA: Academic Press; 2006. p. 504.