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PRINCETON UNIVERSITY

Wind Power

An Energy Technology Distillate from the Andlinger Center for Energy and the Environment at Princeton University

Contributors

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Executive Summary

Wind power may become a mainstay of the future global energy system. It accounted for about five percent of global electricity production in 2017 (compared to about two percent for solar power). Wind power is remote from most people's everyday lives, because it is produced mostly where few people live. The goal of this distillate is to bring wind power closer. We introduce the wind resource, wind power's past and current deployment, the anatomy of turbine blades and generators, its environmental impacts, and the policies and practices that are facilitating its integration into the overall electricity system.

This report is one in a series of "distillates" from Princeton University's Andlinger Center for Energy and the Environment, each of which introduces a single low-carbon energy option and addresses both technology and policy. The distillates seek to be neutral with respect to each option's future, avoiding both hype and negativity. This is the fifth such distillate. The previous distillates dealt with grid-scale storage of electricity, small modular nuclear fission reactors, magnetic confinement fusion energy, and solar power. The intended audience for the distillates is anyone who has an appetite for science and technology; the report is written to be accessible to a wide range of readers.

Four Critical Themes

Four themes affecting the future of wind power recur throughout this distillate: the wind industry is maturing; it is innovative; an important part of its future is offshore; and it is being integrated into electricity grids in spite of wind's variability and limited predictability. We briefly elaborate on each of these findings here.

Maturity

Figure ES.1 shows the annual additions to global wind power capacity from 2001 to 2017, when total globally installed wind power reached 540,000 megawatts. From 2001 to 2012, the additional capacity in each year was larger than the year before, but after 2012 the annual additions were sometimes larger and sometimes smaller, with only a minimal upward trend. The growth pattern in this later period may suggest that wind more resembles a maturing industry than a newcomer.

About one-third of global installed capacity is in China, about one-sixth in the U.S., and the rest elsewhere; these fractions are changing slowly. The average capacity of a new onshore wind turbine now exceeds three megawatts, and it too is climbing slowly. The average height of the tower and its visual impact on a landscape are growing gradually as well. Gradual change is further evidence that the industry is maturing.

Wind power expansion has been helped by significant government incentives world-wide, and many of these incentives are now shrinking. Meanwhile, a host of evolutionary changes in wind power technology are continuing to reduce costs.

Innovation

Today's blade is hollow and made of fiberglass braced by a wood frame, not unlike a giant canoe (see Figure ES.2). Many technological innovations in the wind industry are improving the trade-offs between aerodynamics and structural strength that govern blade design. New materials are offering high structural strength and low weight at lower cost. Blades are getting

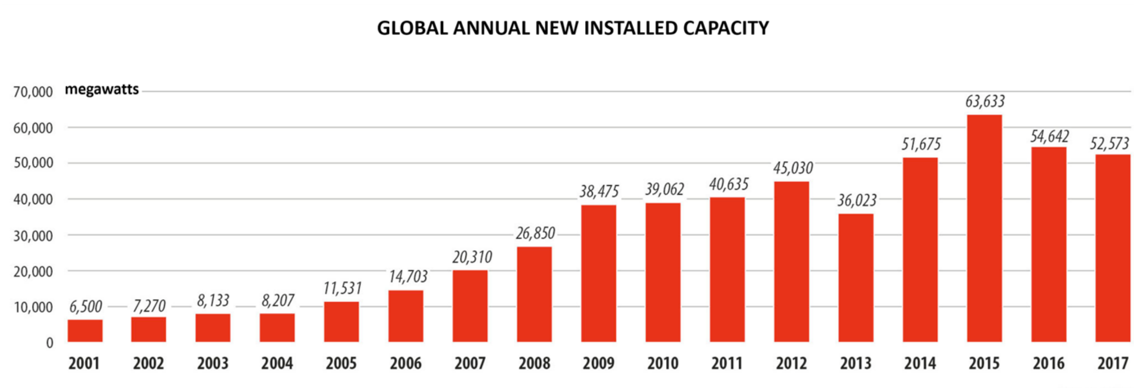

Figure ES.1 (which also is Figure 4.2): Annual additions to global installed wind power capacity, 2001-2017. By the end of 2017, the global total reached 540,000 megawatts. One megawatt is one thousand kilowatts. Source (redrawn): Global Wind Energy Council, http://gwec.net/global-figures/graphs/.

Figure ES.2 (which also is Figure 5.2): A 50-meter blade stored at ground level, being examined by one of the authors (Greg Davies) at the Sherbino 2 wind farm in western Texas. Photo: Ryan Edwards.

longer and are being shaped more cleverly to improve their performance. As a result, new wind turbines are able to produce electricity from winds at both lower and higher speeds than older generations of turbines.

Other technological innovations reflect advancements in the conversion of the energy in the rotating blades into electricity. The blades of a large wind turbine rotate quite slowly, typically taking six seconds to complete one revolution (one-sixth of a cycle per second at their fastest). By contrast, the shaft inside the turbine's electrical generator must rotate far faster to produce the high-frequency required for grid electricity (60 cycles per second in the U.S.). Mechanical gears connecting the blades to the generator can produce this frequency multiplication and used to be present in all wind turbines, but they are prone to wear and require substantial routine maintenance. An alternative is the direct-drive generator, which does away with the mechanical gears and achieves the required frequency multiplication by combining the electrical power produced by many pairs of magnets. These high-performance magnets are shown in Figure ES.3.

Figure ES.3 (which also is Figure 6.5): The manufacture of a permanent-magnet generator. The permanent magnets are the silver brick-shaped objects, arrayed end-to-end along the inner perimeter of the stator; the left hand of the operator standing inside the stator is nearly touching one. Photo: General Electric, https://www.ge.com/reports/where-ge-makes-haliade-turbines/.

Meanwhile, other innovations have driven down the cost of operating a wind farm. Nearly all wind turbines are located in wind farms, in clusters of tens or even hundreds of turbines. A wind farm functions as a single unit regarding its financing, its relationships with local communities, and its negotiations with the grid. Wind farm operators are improving their decisions about the layout of the turbines on a farm, reducing the negative effects on a downwind turbine caused by the wakes of upwind turbines. The operators are also making better use of weather forecasts, and they are reducing maintenance costs by using drones for blade inspections.

The Offshore Frontier

Although offshore wind power currently accounts for about five percent of total global wind capacity, it may conceivably grow over the next few decades to become even more significant than onshore wind. Relative to onshore wind farms, offshore farms access steadier and stronger winds, and they are often closer to coastal cities, where demand is concentrated.

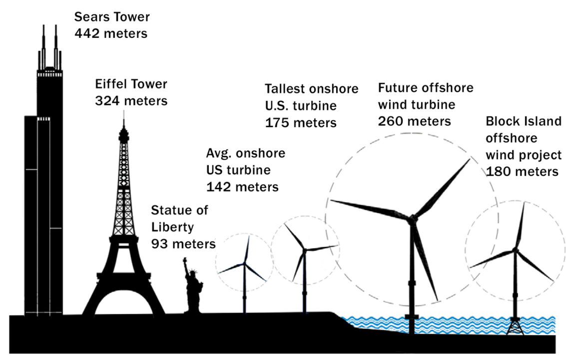

Figure ES.4 (which also is Figure 7.5): Offshore wind turbines are already as large as the largest wind turbines and are slated to become much larger. Wind turbine sizes are compared to the Sears Tower in Chicago, Statue of Liberty in New York City, and Eiffel Tower in Paris. Dashed circle indicates the path of the blade tip. One meter is 3.28 feet. Source: Bumper DeJesus, Andlinger Center for Energy and the Environment.

Almost two-thirds of installed offshore capacity today is located in the United Kingdom and Germany, with China in third place. In the U.S. only one offshore wind farm now operates, off Block Island, Rhode Island, with five six-megawatt turbines. However, several northeastern states are encouraging wind farm construction off their coasts, and a burst of activity may lie immediately ahead.

Costs for offshore wind power are falling. One important reason is that offshore wind turbines are getting much bigger. This change is occurring rapidly, rather than gradually: eight-megawatt turbines are already in production, and 12-megawatt turbines have been announced by several manufacturers. The blades on 12-megawatt turbines will be just over 100 meters long, twice as long as those on the three-megawatt turbines deployed onshore. See Figure ES.4, where the heights of the average and tallest U.S. onshore turbines in 2017, two offshore turbines, and three iconic structures are compared. There are plans for offshore wind farms as large as all but the largest onshore wind farms: their capacity could reach 1,000 megawatts (imagine 80 12-megawatt turbines).

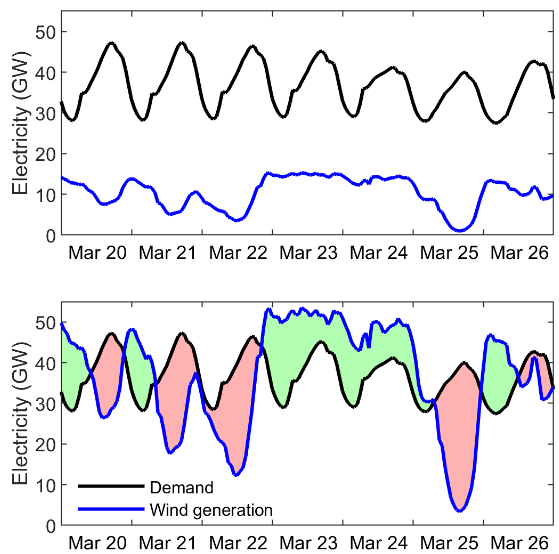

Figure ES.5 (which also is Figure 8.2): *Top:* Actual electricity demand and wind generation in Texas, March 20-26, 2017. *Bottom:* Wind capacity, rescaled to create the counterfactual diagram where the total wind generation that week equals the total electricity demand, and no other changes are made. Green and red shaded areas represent excess wind and a deficit of wind, respectively, when generation is compared with demand. Data source (top panel): Electric Reliability Council of Texas, Hourly Aggregated Wind Output (2018), http://www.ercot.com/gridinfo/generation. Source (bottom panel): Ryan Edwards.

The maximum size of an onshore turbine is determined mostly by the complications of delivering its blades and other major components to the site by road; the use of ships enables delivery of larger and heavier parts, including longer blades. The value of increased size is greater for offshore than onshore turbines, because offshore turbines sit on top of more expensive structures (a platform in deep water rather than a foundation on land) and are more difficult to maintain (access to offshore sites is more complicated). Because maintenance is more difficult offshore, the developer will frequently choose a turbine whose parts last longer and are more easily replaced, even when the turbine's initial costs are greater. The direct-drive generator shown in Figure ES.3 is a case in point, preferentially chosen today for offshore wind farms.

Variability, Uncertainty, and Grid Operation

The integration of wind power (and solar power) into an electricity grid increases the need for grid flexibility, because not only does demand vary, as it always has, but now the grid also hosts only partially predictable, variable energy sources. Both surpluses and shortfalls of electricity supply can arise when wind power contributes a large fraction of a region's total electricity production. Consider the two graphs in Figure ES.5. The top panel compares actual power demand and actual wind power output for one week (March 20-26, 2017) in Texas, when wind power accounted for 28 percent of total power generation. In the hypothetical bottom panel, a simplistic future is imagined for Texas where the same wind-power pattern is preserved but the absolute level of the wind power is raised so that wind output equals total demand. As a result, periods of extra wind alternate with periods where wind power is insufficient. Although no real future will look like the bottom panel, the poor match-up between aggregate demand for power and supply exclusively from variable energy resources is indicative of challenges ahead.

Whenever wind power becomes a significant fraction of total power on a grid, an additional requirement imposed on the wind turbines is to assure grid stability when a sudden change in voltage and frequency (a "fault") occurs, as would be the result, for example, if one of the grid's major power plants goes offline or a major load comes online. The first large wind turbines that produced grid power were so inflexible that they were immediately disconnected when the grid experienced a significant disruptive event. The more recently installed wind turbines with advanced power electronics can stay online during grid disruptions and regulate their output power to keep the grid's characteristics within the narrowly specified ranges. The operator of a wind farm with advanced turbines also contributes to grid stability by coordinating the output of the turbines to constrain within narrow limits both the farm's total output power and the rate at which total power can ramp upward or downward. "Grid friendly" wind power is becoming the new norm.

Article 1: Roadmap

Our distillate has eight articles, each intended to be independent of the others, so that readers with particular interests can read selectively. The first article is this brief *"Roadmap."* Article 2, *"Key Concepts and Vocabulary,"* introduces a few of the concepts widely used to discuss electricity in general and wind energy in particular. It is followed by two articles that discuss realizable and realized wind energy. Article 3, *"The Wind Resource,"* presents the Earth's near-surface winds, as yet only very partially transformed into wind-powered electricity. Then Article 4, *"Current Deployment, Markets, and Incentives,"* discusses actually deployed wind power.

Articles 5 and 6 are the most technical and complement each other. Article 5, *"The Single Wind Turbine: From the Wind to the Blades,"* takes the reader to the site of a turbine in the field to learn about the turbine's performance and the compromises between aerodynamic and structural objectives that have resulted in today's slowly twisted and tapered blades. Then the reader goes inside the tower to see the generator. Article 6, *"The Single Wind Turbine: From the Blades to the Grid,"* completes the sequence of energy transformations that lead from wind to marketable electricity, noting the evolution of the turbine's components over the past few decades driven by modern power electronics.

Article 7, *"Wind Farms,"* reports on the challenges of building and operating a cluster of wind turbines cost-effectively while satisfying the demands of grid operators and the concerns of local communities for social and environmental impacts. Article 8, *"Managing a Grid when Variable Wind is Prominent,"* discusses how the capabilities of wind turbines have been evolving to contribute to grid stability. Article 8 includes a generalizable analysis of wind power's variability based on the frequency of "lulls" of various lengths.

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Article 2: Key Concepts and Vocabulary

We introduce a few underlying concepts and vocabulary for electricity and wind power.

2.1 The Watt and the Watt-Hour

The Watt (The Common Unit of Power)

The rate at which energy is produced or consumed is known as power and is measured in watts. For electrical devices, this energy is in the form of electricity. Some electrical devices (generators) produce electricity and others (loads) consume it. A 60-watt light bulb consumes electricity at the rate of 60 watts when turned on. A toaster making toast consumes electricity at a rate of about 1,000 watts, or 1 kilowatt. The largest jet aircraft engines can produce energy at a rate of about 100 million watts, or 100 megawatts.

We will use both kilowatts and megawatts in this distillate; remember that a megawatt is 1,000 times larger than a kilowatt. We will not use the "gigawatt," which is 1,000 times larger than a megawatt. We will avoid abbreviations: W, kW, MW, and GW, for the watt, the kilowatt, the megawatt, and the gigawatt, respectively.

A new, large land-based wind turbine today would typically be able to produce electricity at a maximum rate of three megawatts; it cannot produce electricity any faster, but in low winds it will produce electricity at a lower rate.

The Watt-Hour (The Common Unit of Energy)

The watt-hour is a unit of energy, which is commonly used to describe amounts of electricity produced or consumed over a period of time. The hyphen in watt-hour means that a multiplication is involved: a multiplication of a power unit (rate of energy production) and a time unit. A 60-watt bulb will consume 60 watt-hours when it is on for one hour and 120 watt-hours when it is on for two hours.

In this distillate, the energy units we will use are the kilowatt-hour and the megawatt-hour; we will not use the watt-hour or the gigawatt-hour. In the text, we will not abbreviate kilowatt-hour as kWh or megawatt-hour as MWh, but will always write them out. Where abbreviations do occur in figures, we remind the reader of their meaning in the caption.

Watts and watt-hours are frequently confused, in part because the watt is one of the few units describing a rate that has a name of its own.[1] If a home consumes 360 kilowatt-hours of electricity in 720 hours (a 30-day month), it consumes electricity at an average rate of half a kilowatt (500 watts).

2.2 Features of Wind and the Wind Turbine

Nomenclature for the Wind Turbine

Figure 2.1 labels the four main components of a wind turbine. The particular image shows a turbine sited offshore in Belgium. The blades are attached to the hub, which is part of the nacelle located at the top of the tower.

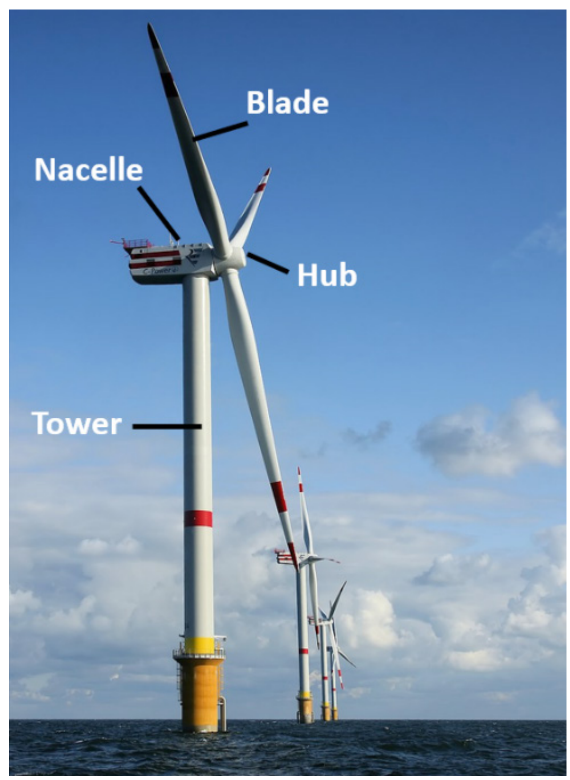


Figure 2.1: The principal parts of a wind turbine. Source: Hans Hillewaert, https://en.wikipedia.org/wiki/Wind_turbine#/media/File:Windmills_D1-D4_(Thornton_Bank).jpg.

[1]Other units that describe rates include the ampere (a rate of flow of electric current) and the knot (a measure of nautical speed).

Wind Speed

U.S. readers know intimately how to think about wind speed in miles per hour. Ordinary walking is more difficult at wind speeds of 30 miles per hour, and signs of the destructive force of wind on trees and structures are likely after winds at speeds of 60 miles per hour have moved through. However, most of the world discusses wind speeds not in miles per hour but in meters per second. We will always report wind speeds in meters per second, but we will not always provide the speed in miles per hour. The conversions between the two units are these:

2.22 miles per hour is 1 meter per second,

1 mile per hour is 0.45 meters per second.

Thus, 30 miles per hour is 13.5 meters per second, and 60 miles per hour is 27 meters per second.[2]

The "Turbine" and the "Farm"

The word "turbine" is used in two ways in the wind industry. In this distillate, the "wind turbine" is the entire system that converts incoming wind to electricity, including the foundation, the tower, and the blades, as well as the mechanical and electrical machinery, mostly located at the top of the tower. The "turbine" sometimes refers, instead, just to the rotating machinery that produces electricity from the mechanical energy of the slow-rotating shaft attached to the blades. The wind turbine viewed as a system used to be called a "windmill," because its principal function was to mill grain by turning a millstone; the change from "mill" to "turbine" emphasizes that its objective now is to generate electricity.

Although the word "windmill' is disappearing, the words used for a collection of wind turbines at a single site still evoke the industry's agricultural origins: it is called a "wind farm." Figure 2.1 shows an offshore wind farm.

Rated Wind Speed and Rated Capacity for a Wind Turbine

Every wind turbine has a specific wind speed, the "rated" speed, which is the lowest wind speed at which it generates power at its full capacity (its "rated" capacity). The turbine is deliberately operated so as to prevent the production of extra power when the wind blows faster than the rated speed. The rated speed is a compromise between capturing as much wind as possible and keeping the cost of the turbine as low as possible.

Capacity Factor, A Performance Index for a Turbine at a Site

The "capacity factor" is a generic concept, applicable to any power plant. It is the actual amount of electricity produced at a power plant, divided by the maximum amount of electricity the plant could have produced if it had run continuously at its rated capacity (over some common period such as a year). In the case of the wind turbine, the capacity factor, as noted above, is tied to the rated wind speed and the actual distribution of wind speeds at a site.

The capacity factor of a wind turbine is affected by the variability of the wind speed at the site: an ideal wind would blow at the rated speed all the time. The capacity factor is reduced as a result of times of low or non-existent winds, downtime for maintenance, and any deliberate reduction in power generation (curtailment) imposed by a grid manager to prevent excess supply.

The capacity factor can also characterize a wind farm, or all the wind in a utility's portfolio, or an entire geographic region. For example, the capacity factor for the entire world's wind power (an average over all the wind power plants) in 2015 can be calculated from estimates that global installed capacity (the total rated capacity for all the turbines licensed to run) was 435,000 megawatts (435 million kilowatts) and global wind production was 834 billion kilowatt-hours.[3] Since there were 8,760 hours in 2015, it follows that 3,810 billion kilowatt-hours of electricity would have been produced if the turbines had run at full capacity all year. Dividing 834 by 3,810, the capacity factor for the world's wind power in 2015 was 22 percent.

Another way to express this result is to note that 22 percent of the 8,760 hours in a year is about 1,900 hours. Therefore, global production was equivalent to production at full capacity for about 1,900 hours, and no electricity production during the rest of the year.

Capacity factors are much higher than 22 percent for recently installed turbines, excellent sites, and well-functioning electricity markets.

Efficiency, A Performance Index for a Turbine Determined by the Device

The efficiency of a turbine is a measure of its performance that is complementary to the concept of capacity factor. The efficiency quantifies how well the incoming energy in the wind is converted into electricity, while the capacity factor is largely determined by the

[2]One hour is 3,600 seconds, and one mile is 1,609 meters (1.609 kilometers). Dividing (3,600 seconds per hour) by (1,609 meters per mile) equals (2.22 miles per hour) per (meter per second).

[3]World Energy Council - World Energy Resources Wind | 2016

characteristics of the wind where the turbine is located. A typical efficiency for a large modern turbine is about 40 to 50 percent. To state this in other words, imagine a circle traced by the tips of the blades of a wind turbine as they turn. A 40 percent efficient wind turbine produces an amount of electricity equal to 40 percent of the kinetic energy in the wind that would strike the area within that circle if the blades weren't turning.

Pitch and Yaw

A wind turbine can change its output by changing the angle between the blades and the incoming wind (the "pitch" of the blades). It can respond to a change of wind direction by turning the nacelle to face the wind using its "yaw" motors.

Curtailment

A grid operator can require that the power output of a wind turbine be reduced when total electricity production from the whole system would otherwise exceed total consumption and contractual or other barriers constrain the reduction of production from the other resources on the grid. These "curtailments" can arise when turbines are built ahead of transmission capacity or when the rules of a grid prioritize other sources ahead of wind. Curtailments also result when wind forecasting has under-predicted actual production and the grid cannot accommodate the excess. Because of the low marginal cost of wind power, grid operators and wind power developers seek to minimize curtailments.

Article 3: The Wind Resource

Winds available for wind power today are within the first few hundred meters of the atmosphere. They carry significant amounts of energy, relative to the amount of energy used by human beings. This article seeks to convey the physical characteristics of these winds – both their regularity and their variability over various lengths of time and over various distances. It concludes with a brief history of when humans began understanding wind's characteristics.

3.1 Where Does the Wind Blow?

Wind surrounds us, and we have all experienced its effects. Sometimes strong winds are welcome, as on a hot summer day, but if they get too strong, being outdoors can become unpleasant. This personal "observational experiment" with wind informs us that some locations experience much stronger winds than others, and that even at a specific location wind speed varies a lot. Quantitative measurements of wind using accurate sensors, when combined with computer modeling, can explain much of this variability.

The distinct patterns of airflow that the atmosphere displays when averaged over a decade or more are consistent enough to allow mariners to rely on them to sail the world. Figure 3.1 below shows the modeled main patterns of spatial variability of the average global wind speed, using observational data to improve the model's accuracy. These are averages over the seventy-year

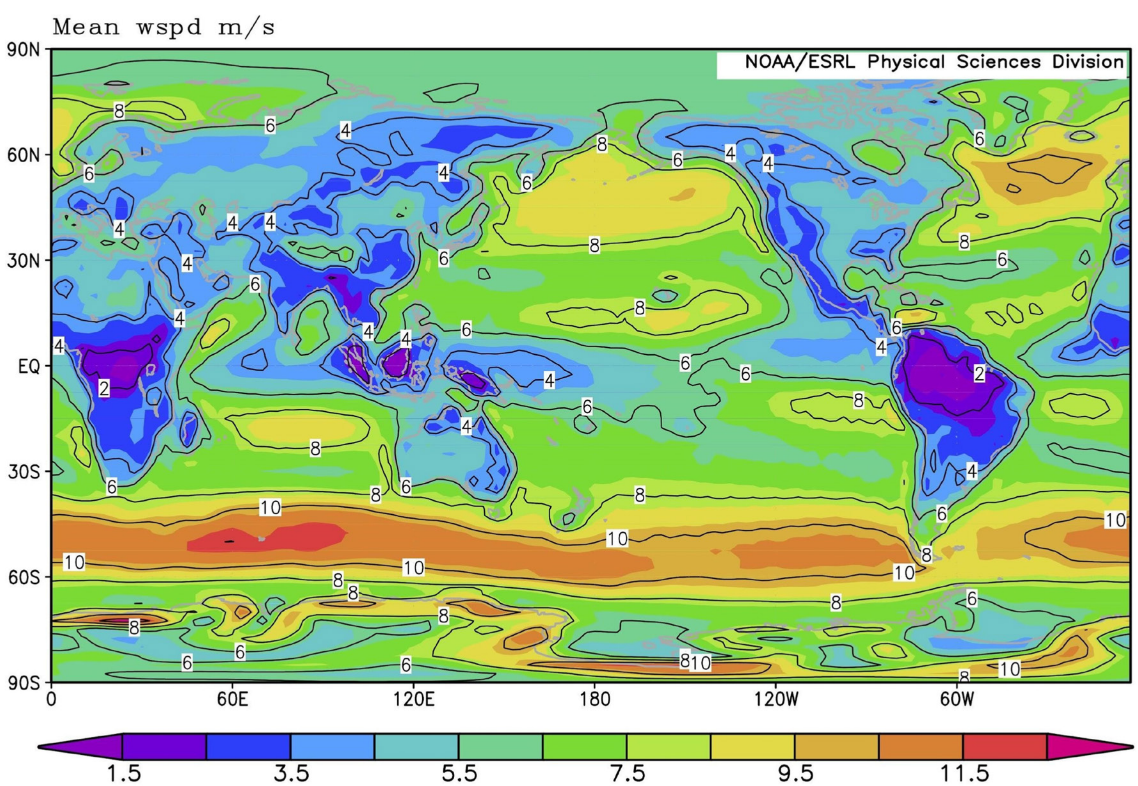


Figure 3.1: Average wind speed (in meters per second) near the Earth's surface (at about 50 meters altitude), calculated from the climate simulations by the National Centers for Environmental Prediction for Jan 1948 to Jan 2018. The horizontal axis indicates east and west longitudes (for example, 60 degrees east) and the vertical axis shows latitudinal degrees from the equator north and south. The integers on the map are the wind speeds, in meters per second, of the corresponding contours, and the colors are keyed to the color code below the map. Source: National Oceanic and Atmospheric Administration, Earth System Research Laboratory, https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html.

period from January 1948 to January 2018 for wind speeds about 50 meters above the Earth's surface.

A few patterns quickly come to one's attention:

1) General wind patterns are strongly influenced by continents, and the contours of average wind speed track the land-sea boundary in coastal areas.

2) Near the Earth's surface, winds over oceans are much stronger than over land. This is something many would have experienced when visiting the shore or islands in the middle of the ocean, or when sailing. Stronger winds over the oceans are mainly the result of the "smoother" liquid water surface that creates less drag on overlying wind currents. Land surfaces are rougher as a result of their mountains, forests, and even buildings and factories. All of these topographic features of the land slow down winds significantly over continents. But these same obstacles can funnel airflow to create local areas of high winds suitable for building wind farms. The near absence of land in the southern hemisphere at latitudes of about 40 degrees south is the reason behind the band of strong winds at these latitudes, commonly called the "Roaring Forties."

3) Even if one ignores this "Roaring Forties" band, significant changes in latitude affect wind speeds. For example, regions near the equator are characterized by low winds, while mid-latitudes experience much faster airflow.

4) The overall range of annually-averaged wind speeds is from about two meters per second (roughly five miles per hour) in the interiors of South America and Africa near the equator, to about 11 meters per second (roughly 25 miles per hour) in the Roaring Forties.

If we now examine the U.S. specifically, instead of the whole world, we can observe spatial variability at a smaller scale (see Figure 3.2). Average annual winds are shown, now at 80 meters above the surface, where wind turbines are typically installed. (Winds at 80 meters are roughly 10 percent stronger than at 50 meters.) Topography evidently has a large influence on wind patterns over land: mountains funnel wind flow and induce large spatial variations in wind patterns; stretches of flat land allow wind to gain speed; and the boundary between land and oceans creates its own patterns. A wide band of high winds with average annual speeds nearing 10 meters per second (22 miles per hour) runs north-south through the Great Plains to the east of the Rocky Mountains. The map also shows how quickly wind responds spatially to a change in the underlying surface topography. For example, observe the rapid changes in average wind speed near land-water transitions over the Great Lakes and at many locations offshore quite close to the coasts, again due to the smoothness of water surfaces.

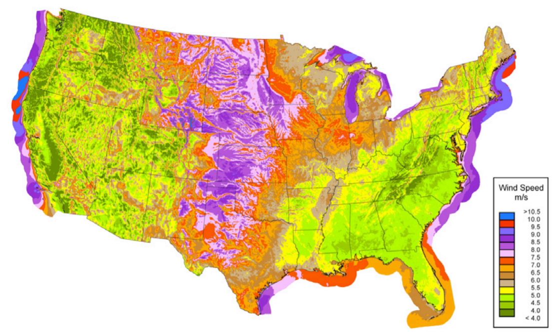


Figure 3.2: Estimated average annual wind speeds for the U.S. at 80 meter altitude, onshore and offshore. Source: National Renewable Energy Laboratory, https://www.nrel.gov/gis/images/80m_wind/awstwspd80onoffbigC3-3dpi600.jpg.

Notice that winds off the coasts of Florida are significantly weaker than those off the coast of New England. In the next few sections we will explain how this pattern of strong latitudinal variation of atmospheric flow emerges and how the wind varies in time at a fixed location.

3.2 Why Does the Wind Blow?

The movements of air that we call wind are driven by differences in pressure that have their origin in the heating of the Earth's surface by the Sun unevenly – more near the equator and less near the poles. This imbalanced heating creates significant temperature differences in the atmosphere, and masses of air cannot stand still when they experience such gradients. There are similarities to water boiling in a pot, where the water heated at the bottom becomes less dense, rises, and mixes with cooler water to homogenize the temperature. Geophysical flows of air (and ocean water) are also seeking to homogenize the Earth's temperature, but they can never fully succeed. In the case of wind, air at the equator, heated by contact with the hot Earth surface, expands and rises, while polar air cools and sinks.

A Rotating Planet

If a planet mostly like ours were not rotating, its major surface winds would blow toward the equator from both poles. At the equator air would rise to the top of the troposphere, called the tropopause, where it would be redirected poleward. (The troposphere is the lowest layer of the atmosphere; it extends from the Earth's surface to a height of 11 to 18 kilometers, a little higher than the Earth's highest mountains.) At the poles air would flow downward to the surface to close the cycle; such a cycle is called a convection cell. This convection cell would convey heat from the equator to the poles very efficiently, since the winds would be perfectly aligned along lines of constant longitude (ignoring continents for now).

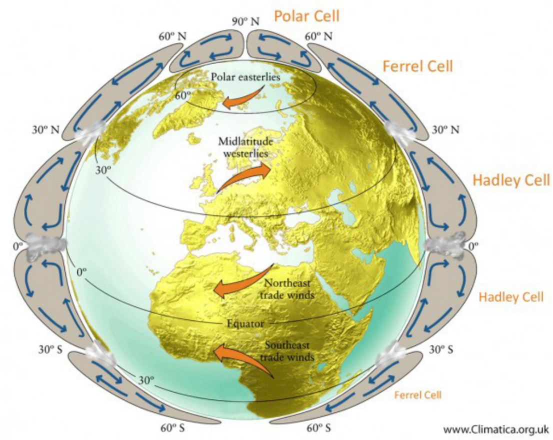


Figure 3.3: Long-term average circulation patterns for our rotating Earth, highlighting the climatic features of the winds. The circulation in each hemisphere is characterized by three cells (loops of air motion). Source: Climatica, http://climatica.org.uk/climate-science-information/earth-system.

But the Earth does rotate, and very fast. The Earth's surface at the equator is moving at a staggering 463 meters per second (1,036 miles per hour), and this rotation affects the wind patterns substantially. The rotation of the Earth results in three convection cells in each hemisphere, as shown in Figure 3.3. The Hadley cell is found at latitudes near the equator. At the highest latitudes is the polar cell, and at mid-latitudes the intermediate circulation is called the Ferrel Cell. These three cells, working together, still convey heat from the equator to the poles, but less efficiently than as a single cell.

Wind Patterns

The Earth's rotation affects the wind patterns seen by a wind turbine rotating with the Earth's surface: the winds are no longer north-south (longitudinally) aligned. Instead, they acquire a very significant east-west (latitudinal) component, larger than the north-south component. In the northern hemisphere, the Earth's rotation causes a rightward deflection of the surface winds generated by the three cells, while in the southern hemisphere surface winds veer leftward. This helps to explain why the Earth's wind patterns are organized in largely self-contained "belts" that wrap around within given latitude ranges. Someone moving from one latitude to another (moving north-south) can experience large shifts in wind patterns (as illustrated in Figure 3.1).

These belts and circulations shift with the season. Figure 3.3 depicts their conditions at the March and September equinoxes; they move southward from September to March (when the sun's radiation is stronger in the southern hemisphere), and northward from March to September.

Winds in the belt at the equator blow primarily westward. These are the "trade winds" that enabled Europeans, including Columbus, to sail to the Caribbean and Brazil. By convention, a wind blowing westward – that is, toward the west – is called an easterly wind, named for the direction from which the wind is coming. So, the trade winds are northeasterly in the northern hemisphere and southeasterly in the southern hemisphere. A second important belt is the westerlies belt that dominates mid-latitudes in both the northern and southern hemispheres. Columbus sailed back to Europe on a route much further to the north than his outward journey in order to ride these westerlies. The final significant belt is the polar easterlies; these are so close to the poles that they are not very applicable to marine navigation, although the melting of the polar sea ice might change this.

The Wind Rose

The combination of background climatology (circulations and belts) and geographic factors (e.g., topography and proximity to coasts) determines whether a given location is a good site for extracting power from the wind. A widely used way to illustrate site-specific climatology is the "wind rose." For any single location, a wind rose displays how often wind comes from each direction, and the distribution of wind speeds for that direction.

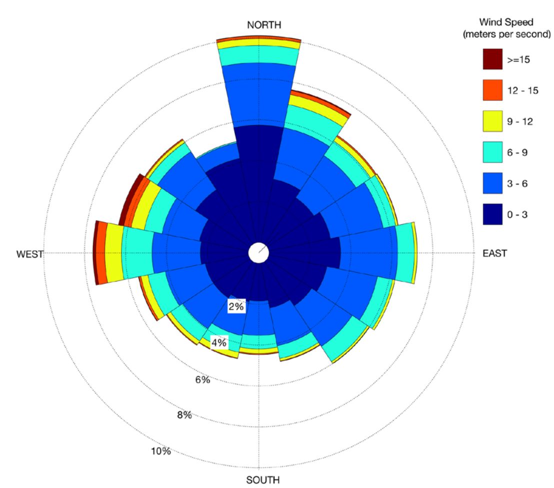


Figure 3.4: Wind rose for Boulder, Colorado, U.S., with data from 2015. The radial extent of a colored element of the wind rose in a given direction is proportional to the fraction of the time that wind comes from that direction within a particular range of wind speeds. Data are for 100 meters above ground, obtained from the Boulder Atmospheric Observatory. Source: National Oceanic and Atmospheric Administration, Earth System Research Laboratory, https://www.esrl.noaa.gov/psd/technology/bao/.

Figure 3.4 shows a specific wind rose – for the Boulder Atmospheric Observatory, a tall tower in Colorado, U.S. The wind speed (in this case, measured at 100 meters above the ground) is shown for six ranges of speeds in six colors, starting with speeds less than 3 meters per second and ending with speeds higher than 15 meters per second. The incoming wind direction is similarly divided into sixteen ranges of angles. The larger a box, the more the wind comes from that direction and at that speed. For example, wind blows from the north about 10 percent of the time, but more than half of these winds have speeds less than 3 meters per second. Most wind speeds for this location are between 0 and 6 meters per second. The most frequent winds are the northerlies, but the strongest winds blow from the west.

The wind rose is particularly convenient and easy to interpret. Wind speed data can help developers decide if a site is appropriate for a wind farm and to select an appropriate turbine, while data about wind direction can help design the layout of its turbines.

3.3 Why Does the Wind Blow Chaotically?

In introducing Figure 3.1 we commented that the wind patterns shown are averages over a decade or more. Contributing to these average winds, including the three circulation cells, are the Earth's land-sea boundaries, its topography, and its speed of rotation. These average winds are features of the Earth's climate, which is the state of the atmosphere that one can observe if winds, temperatures, precipitation, and other pertinent variables are averaged over many years.

But continents and mountains do not move on time scales relevant to wind, and the Earth's speed of rotation is essentially constant. Nonetheless, the world's wind patterns are not stable. They break down into smaller air masses that move around chaotically. Why do winds vary so chaotically in speed and direction from day to day, and even hour to hour, creating what we call weather?

Weather

From personal experience, we know that weather varies to a considerable extent and appears unpredictable, especially more than several days ahead. Figures 3.1 to 3.4 reflect only the wind climatology, where the many short-term fluctuations of the weather are averaged out. In some regions of the globe the weather fluctuations are much weaker than the patterns of climatic circulation. This is the case near the equator, where climatic patterns dominate. Intrepid sailors have depended on this regularity for their travels. However, the absence of weather fluctuations also means the winds are generally calmer, leading to periods commonly referred to as doldrums, very slow wind speeds that can trap sailing ships for multiple days.

In other regions such as mid-latitudes, the climatic circulation breaks down. The winds are stronger and their fluctuations from the average climate are larger. The resulting motions of air masses (the weather systems) are more chaotic. Chaos refers to a characteristic of a system where small changes in its current state can lead to much larger differences in future states. The length scales of these weather systems range approximately from 10 to 1,000 kilometers, and they persist for many weeks in the atmosphere, continuously in motion. Because a weather system requires from two days to two weeks to pass over a given location, that location generally experiences this weather for only a fraction of the system's lifespan. The two most important factors that control the airflow in these systems are: (1) the Earth's rotation (again), and (2) differences in air pressure between a given air mass and adjacent ones (a weather system's highs and lows).

Air pressure in the atmosphere reflects air temperature and airflow. It typically varies by about one tenth of one percent over a distance of 100 kilometers, but that is more than sufficient to modulate the weather by accelerating the air masses significantly. These pressure differences create a flow between adjacent air masses.

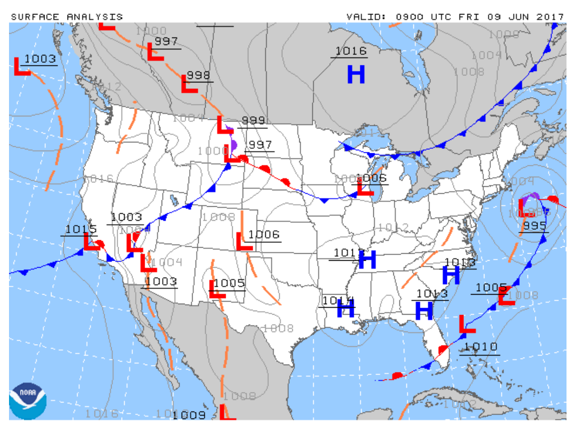


Figure 3.5: A typical weather map for the U.S. showing the complex weather patterns at a particular time and date, in this case Friday June 9, 2017, at 10:26 Universal Time Coordinated (formerly, Greenwich Mean Time). The thin grey contours are curves of equal pressure. Source: National Oceanic and Atmospheric Administration, National Weather Service, https://www.weather.gov/zjx/sfc_analysis.

Weather Maps

Movements of air over periods of hours to days are captured by weather maps. As expected, there maps are more complicated than maps of the average climate, because they display the patterns of air pressure and wind at a particular moment. Consider Figure 3.5, which shows a weather map for the continental U.S. at a particular time on June 9, 2017. Locations of maximum and minimum pressure are marked as a blue H for a high-pressure system (an air mass that has originated where the vertical cell circulation is downward) and a red L for a low-pressure system (originating where the vertical cell circulation is upward). Air flows from regions of high pressure toward regions of low pressure, but the Earth's rotation prevents straight-line flow from high to low. Instead, the winds spiral almost parallel to the lines of constant pressure (known as isobars). In the northern hemisphere the winds move clockwise and slightly outward as they circulate around from highs, and anti-clockwise and slightly inward around lows. (These directions of rotation are the opposite for highs and lows in the southern hemisphere.) In Figure 3.5, the Southeastern U.S. is experiencing high-pressure air, while low pressures dominate over the West.

The blue and red curves show "fronts," which are boundaries between air masses with substantially different temperatures; at fronts, there is often rainfall. The motion of these fronts tracks the motion of the air masses and their boundaries. The blue curves are cold fronts, where cold air is displacing warmer air. The red curves are warm fronts where the opposite is occurring. The curve with both red and blue is a stationary front that is not moving. When two fronts merge, a complex meteorology is the result. The isobars that connect points of constant pressure on the map reveal the strength of the wind. Isobars that are closer together imply greater pressure gradients and therefore stronger winds (e.g. around the low off the coast of New York). The Pacific Northwest is experiencing light winds on this particular day. The dashed orange lines are low-pressure "troughs" (equivalent to the valleys on a topographic map) and often bring rain.

Weather maps like Figure 3.5 also inform us, indirectly, about how far away from a generally windy place is there a calm place, at various times of the year. If the wind power generated at two places where the wind speeds are often different can be combined, a less variable total wind power output will result, which will reduce the problems created by unpredictable and variable electricity production.

The correlation between the strengths of winds at two different locations is related to the typical size of the chaotic air masses, which, as noted before, range from 10 to 1,000 kilometers. So, we expect locations that are less than 10 kilometers apart to be strongly correlated, and locations that are more than 1,000 kilometers apart to be very weakly so. This has practical significance for wind power: combining the wind power from two locations far from one another may require the construction of new electric power transmission lines. Transmission lines may need to extend hundreds of kilometers from one another, or more, to create a substantial reduction in the variability of some wind power resources.

3.4 When Does the Wind Blow, and How Variably, at a Single Location?

In the previous section we explored variations from place to place in the wind at a given moment. The other kind of variation is from one time to another at the same place.

The variability of wind in time at a single location occurs on scales ranging from a few minutes to a few days to entire seasons. The strongest variability and the one most relevant for wind energy is the one emanating from weather systems. Consider one of the smaller weather systems, about 10 kilometers in size, moving past a wind turbine at a speed of 5 meters per second. It would affect the turbine for about 2,000 seconds, or about half an hour. By contrast, one of the largest weather systems, spanning 1,000 kilometers and moving at the same speed, would affect the turbine for about two days.

Throughout the period of passage of a single air mass, a wind turbine generally produces electricity at a rate that varies rather smoothly in time. The fastest variations in output occur when a weather front separating two air masses passes by. These fronts cause fast decreases or increases in wind speed ("ramps") that are hard to predict accurately. As an example of a ramp, Figure 3.6 shows a three-hour period from the Boulder, Colorado tower data (the same data as in Figure 3.4). The wind speed ramps up quickly and exceeds 20 meters per second around 1:30 AM, only to drop back equally rapidly to less than 5 meters per second an hour later, before rising again an hour later to over 15 meters per second.

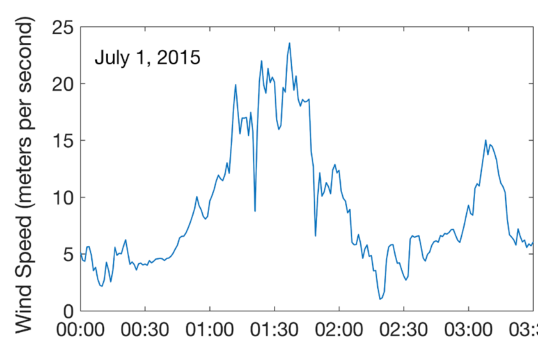


Figure 3.6: Wind speed over a three-hour period, on July 1, 2015 in Boulder, CO. These data are measured at 100m above ground at the Boulder Atmospheric Observatory. Data source: National Oceanic and Atmospheric Administration, Earth System Research Laboratory, https://www.esrl.noaa.gov/psd/technology/bao/.

In many locations, wind speed varies over the course of a day predictably. During the day, the Sun heats the Earth's surface, which causes strong vertical mixing that evens out the variations of wind speed in the vertical direction, accelerating the wind near the surface and decelerating it further above. Nighttime conditions create the opposite effect, reducing the vertical mixing and creating stronger variability of the wind with height. This vertical mixing is produced by turbulent eddies and gusts, which can cause wind variations at time scales ranging from minutes down to thousandths of a second. One result is fast changes in wind speed at sunrise and sunset, when vertical mixing is changing rapidly.

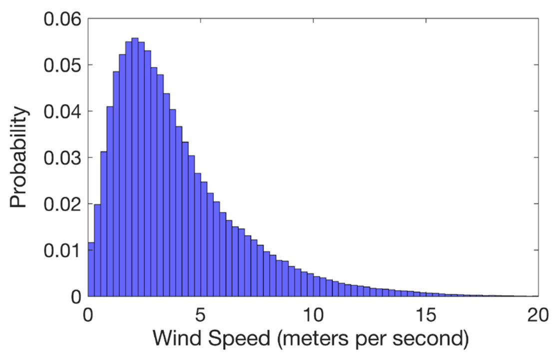


Figure 3.7: Distribution of wind speeds for 2015, at 100 meters above ground, measured near Boulder, Colorado. Data source: National Oceanic and Atmospheric Administration, Earth System Research Laboratory, https://www.esrl.noaa.gov/psd/technology/bao/.

Winds also often demonstrate predictable seasonal variability, as shown by the belts and circulations of the global climate in Figure 3.3. These features move northward and southward with the season, altering the background climatological wind and the stability of the climatic circulation. These changes, in turn, affect the formation and properties of the chaotically moving air masses. One result is that winters, for each hemisphere, are almost always windier than summers.

However, information about the range of wind speeds at a given location is also critically important. The fastest recorded wind speed near the Earth's surface was 113 meters per second (254 miles per hour). It was a gust lasting only seconds, measured during Tropical Cyclone Olivia on Barrow Island, 50 kilometers (30 miles) offshore in Western Australia on April 10, 1996. The same cyclone generated winds sustained for ten minutes that exceeded 54 meters per second (120 miles per hour). In general, tropical cyclones (including hurricanes) and tornadoes generate the strongest winds on the planet, but only for short periods of time.

While a lot of energy can be generated from the highest winds, they are very rare, and it makes little financial sense to build wind turbines that target such extremes. Instead, wind turbines are designed to operate in wind conditions ranging, typically, from 3 to 25 meters per second (7 to 65 miles per hour). A site is chosen for wind farm development based on detailed local data. We turn now to how these data are developed and displayed.

As seen in section 3.2, a wind rose depicts the probabilities of wind speeds falling in a given ranges of values. It thus combines the climatic mean, weather variability, and local geographic factors for that site. A simpler way to display wind speed (which, however, does not reveal wind direction) is seen in Figure 3.7, where the height of each bar shows the frequency at which the wind speed at the site falls within a narrow range of wind speeds. Here, for example, the most frequent wind has a speed near two meters per second.

Typically, for a site to be viable for a commercial wind farm, the average wind speed at turbine hub height should be greater than 7 meters per second (much higher than for the location in Colorado in Figure 3.7). When the histogram is "skewed" (that is, when it is not symmetric for high and low values), the average value does not equal the most likely value (the value with highest probability). Wind-speed histograms are never symmetric: both the average and the peak value of the distribution are always closer to zero meters per second than to the highest measured value. An ideal wind site would have a high average (more production) and a narrow range (better predictability).

The full range of the histogram (minimum to maximum) will be quite wide for any site, since zero wind will invariably be recorded sometimes and very strong winds (during hurricanes or tornados, for example) are also possible. The full range is thus not very useful information to estimate overall wind energy production: the rare "tails" of the curve tell us little, compared to the shape of the central part where the more likely values are concentrated.

Near the Earth's surface, the range of most wind speeds is from 1 meter per second (2 miles per hour, calm) to 10 meters per second (22 miles per hour, somewhat windy). But at 80 meters above the surface, winds are about 3.5 times stronger than at 2 meters, and thus the corresponding range would reach 35 meters per second (almost 80 miles per hour). Most commercial turbines are designed to operate between 3 and 25 meters per second (between 7 and 55 miles per hour) and to stop producing power (switching to "safe mode") above 25 meters per second.

3.5 Forecasting the Wind and Implications for Operating the Electric Grid

For grid operation, the wind farm operator needs to know how much electricity to offer and the grid operator needs to know how much to expect, over the coming hour, day, and week. Both lose out when wind forecasting goes awry. The grid operator requires commitments from every energy source to provide specific amounts of power at specific future times. From these commitments, the grid operator develops "commitment schedules" for about one day ahead. As "real time" gets closer, the grid operator updates the schedule for the following four-to-six hours and then for the coming hour. Farm operators are not in as much control of future production as most others on the grid. When the time arrives to deliver the electricity, a wind generator might be producing more or less than it had committed to provide, due to forecast errors.

What is needed by both the grid and farm operator is accurate information about future winds at a site. The well-behaved climatological averages captured by wind roses and wind-speed histograms, which guide farm design, become of secondary importance. The required capability is weather forecasting.

Weather forecasting is improving thanks to increasingly sophisticated models and observations that capture the dynamics of chaotically moving air masses. As noted above, chaotic weather systems are highly sensitive to their starting conditions and to minute details of their motions, making it difficult, but not impossible, to predict how they will play out over time.

The general rules of chaos theory were discovered and formulated first by a meteorologist, Edward Lorenz, in the 1960s, while he was researching atmospheric dynamics. One can think of a chaotic system as a road with many forks: at each fork where there is the choice to go either left or right, and the choice can lead to two very disparate final locations. Even with the help of supercomputers, the limited ability to describe the initial state of the weather restricts the quality of predictions, leading to models that potentially go the wrong way at a fork. Resulting errors can underestimate or overestimate the strength of a future wind, or alternatively they can get the magnitude of some future wind right but its time of arrival wrong (for example due to an error in capturing the time of arrival of a front). Modern-day meteorological forecasting, which relies on simulation codes running on massive computational infrastructure, aims to compensate for these limitations by incorporating into models a wide range of observational data. The result, over the past two decades, has been significantly improved descriptions of the atmosphere's initial state. The other two major contributors to improved weather forecasting are advances in the description of the physics embedded in these models, and better computing resources. More simulations with finer spatial resolution can now be run (either multiple models or the same model run many times), improving the value of the average of the various outputs. However, despite these advances, forecasting remains imperfect, and weather prediction errors can never be expected to be eliminated altogether. A realistic aim is to continue to reduce prediction errors by improving the models used in forecasting and the estimates of their uncertainties, so that farm operators and grid operators can know how much confidence to place in a given forecast.

The simplest method for predicting the weather assumes that the wind at some location will not change. Known as the persistence method, it is more accurate than the outputs from weather forecasting models for very short time periods and specific sites. "Improvement over persistence" continues to be used as a metric of how well a model performs. For a typical site, the most sophisticated numerical weather prediction models today outperform the persistent method after the prediction period exceeds about six hours. For winds a few days ahead, weather forecasters can predict wind speeds at mid-latitudes reasonably well, despite the fact that such wind speeds are usually very different from the average values indicated in Figures 3.1-3.4.

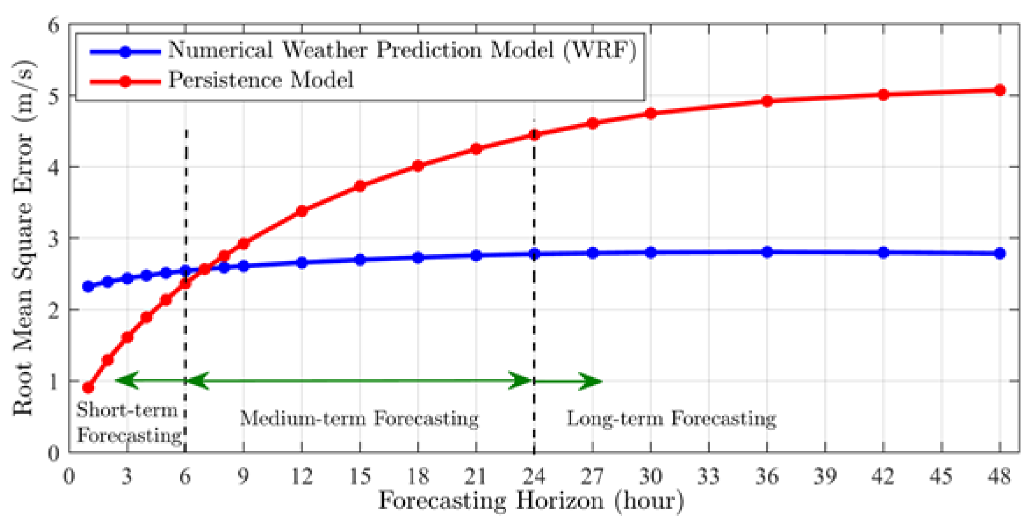


Figure 3.8: The accuracy of the persistence method and a numerical weather prediction model are compared for a specific site. The "root mean square error" on the vertical axis measures the average inaccuracy of a forecast methodology: higher values reflect more inaccurate forecasting. The persistence method predicts that the wind speed will be the same from one hour to the next. The numerical weather prediction model shown here is from the National Center for Atmospheric Research. The data and predictions being compared are from January 2012 at the CHLV Virginia Buoy, a data station off the coast of Virginia near the mouth of the Chesapeake Bay. This hindcasting exercise was made using the 2017 version of the Weather Research and Forecasting Model. For a forecasting horizon of less than six hours, the persistence method performs better.

Figure 3.8 makes this point. It compares a U.S. numerical weather prediction model from the National Center for Atmospheric Research (blue curve) with the persistence method (red curve). The vertical axis measures the inaccuracy of the forecast (a higher value is a more inaccurate average forecast). The persistence model is more accurate than the complex weather model when the forecast is for the wind speed less than six hours ahead. Other weather prediction models give broadly similar results.

Numerical weather-forecasting models, like the European and American Weather Models, are steadily improving. Also under development are "statistical models" that use machine learning to recognize patterns of change in site-specific multi-year data. Moreover, the blending of purely statistical approaches and numerical weather models is currently an active research topic, and aggregate forecasts have shown the ability to beat what each approach can accomplish on its own.

Fast ramps in wind speed are a frequent feature of winds when a front passes by, or when a rapid change in the heating of the Earth's surface (e.g., during sunrise and sunset) modifies atmospheric turbulence. One of the open challenges in forecasting is to predict these ramps accurately. Numerical weather prediction models have a hard time capturing ramps, while the persistence method, on its own, obviously, completely misses them. Much desired is a methodology for short-term forecasting that can capture ramps, or at least can warn of an increased probability of their occurrence.

3.6 Coda: A Brief History of Understanding the Wind

Figuring out how to think about air was a major scientific achievement of the 17th century.

The initial development of technologies to serve human needs is often based on intuition, and only later does a deep understanding of the underlying physical laws emerge. Wind technologies are no exception. Early humans built aerodynamically shaped arrows and harnessed the winds to sail over the seas and to mill grains. They did not know, and did not need to know, that air is a substance which has mass and is therefore subject to large-scale forces.

Hero (or Heron) of Alexandria (~ 10–70 AD), in his treatise on pneumatics, was probably the first scientist to postulate that air is a fluid, that is, a form of matter like water or oil. He is also credited with the first design of a device to harness wind energy to power a machine, a wind organ. However, science had to wait until the 17th century for Galileo Galilee (1564-1642) and Evangelista Torricelli (1608-1647) to provide experimental proof of the nature of air. Torricelli was the first scientist known to have provided a description of the atmosphere that is consistent with current understanding: "We live submerged at the bottom of an ocean of air." He also described air motion: "Winds are produced by differences of air temperature, and hence density, between two regions of the Earth."

More than a century earlier, Leonardo Da Vinci (1452-1519) had laid the basis for experimental fluid mechanics, showing the value of formulating theories and making deductions based on observations rather than on pure thought. Modern wind engineering also owes much to Sir Isaac Newton (1642-1726), who formalized and developed the core concepts and physical laws that, when later applied to fluids, gave us the equations we still use today to model weather and climate at all scales: how air moves, what controls its speed and direction, how its properties change with altitude, and how it is slowed down by the Earth's surface. The same equations are used to design the aerodynamics of airplanes and cars. Finally, given how important the Earth's rotation is, as outlined in this article, credit is due to Gaspard-Gustave de Coriolis (1792-1843), who formalized mathematically the way the Earth's rotation affects how the motion of matter, including air, is perceived by an observer on Earth.

Article 4: Current Deployment, Markets, and Incentives

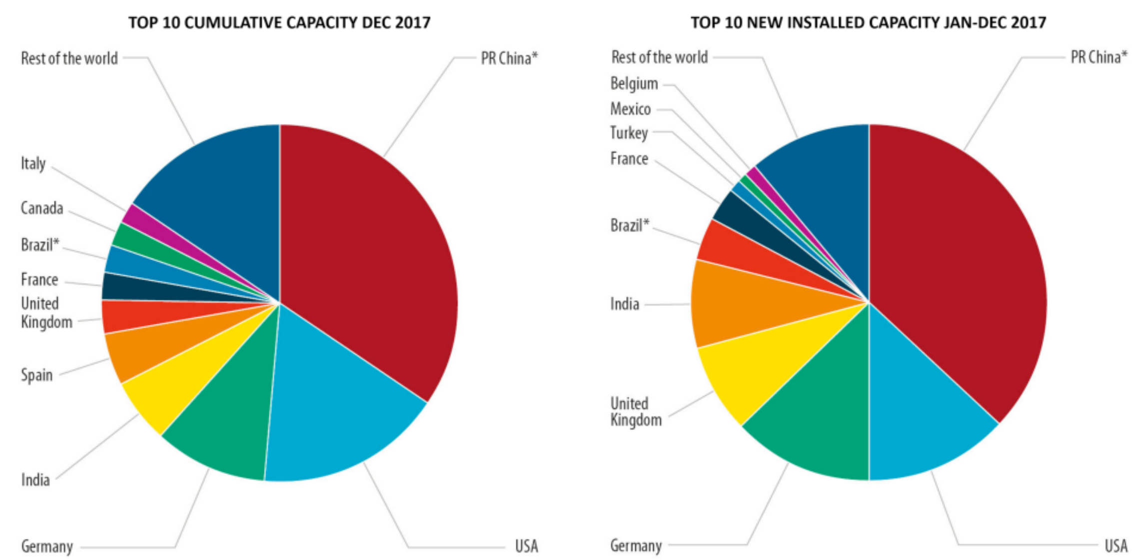
Wind power has expanded across the world to the point where it is a significant source of electricity in many regions. This article looks at the growth that has occurred, considering both installed capacity and actual generation, globally and for the top countries. The geographic distribution of projects within the United States is also described. We conclude with discussions of specific projects.

4.1 Wind Capacity and Generation

Wind Capacity, Globally and for the Leading Countries

At the end of 2017, the total global installed wind capacity was 540,000 megawatts. Its distribution across countries is seen in Figure 4.1, left panel. Additions to global capacity during 2017 are seen in Figure 4.1, right panel. Also shown are the percentages for the top ten countries ranked by total installed wind capacity.

The two pie charts in Figure 4.1 look similar. China accounts for about a third of both total and new global capacity. The U.S. and Germany are in second and third place in both cases. Spain, Canada, and Italy are



Country	MW	% Share
PR China*	188,232	35
USA	89,077	17
Germany	56,132	10
India	32,848	6
Spain	23,170	4
United Kingdom	18,872	3
France	13,759	3
Brazil*	12,763	2
Canada	12,239	2
Italy	9,479	2
Rest of the world	83,008	15
Total TOP 10	**456,572**	**85**
World Total	**539,581**	**100**

Source: GWEC

Country	MW	% Share
PR China*	19,500	37
USA	7,017	13
Germany	6,581	13
United Kingdom	4,270	8
India	4,148	8
Brazil*	2,022	4
France	1,694	3
Turkey	766	1
Mexico	478	1
Belgium	467	1
Rest of the world	5,630	11
Total TOP 10	**46,943**	**89**
World Total	**52,573**	**100**

Source: GWEC

Figure 4.1: *Left:* Total installed wind capacity in 2017, globally and for the ten leading countries. *Right:* New installed wind capacity in 2017, globally and for the ten leading countries. "MW" is megawatts. Source: Global Wind Energy Council, http://gwec.net/global-figures/graphs/.

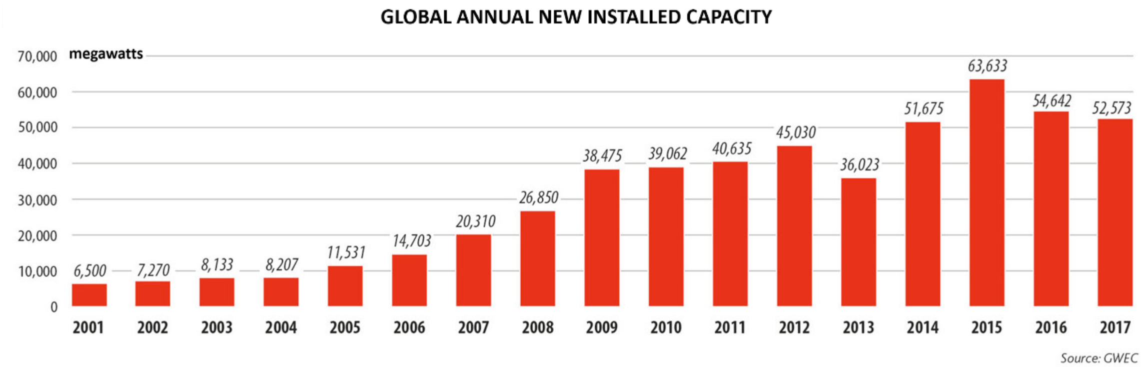


Figure 4.2: Annual additions to global installed wind power capacity, 2001-2017. By the end of 2017, the global total reached 540,000 megawatts. One megawatt is one thousand kilowatts. Source (redrawn): Global Wind Energy Council, http://gwec.net/global-figures/graphs/.

missing from the top ten in new capacity, even though they are present in the top ten for total capacity. Turkey, Mexico, and Belgium have taken their place in the rankings for new capacity.

These data are from the annual report of the Global Wind Energy Council. The same source reports that cumulatively 340,000 wind turbines were deployed as of 2016, when global installed capacity was 490,000 megawatts, from which it follows that the average capacity of these wind turbines was one and a half megawatts.[1]

Figure 4.2 shows annual incremental additions to global capacity over the preceding 17 years. Since 2009, growth has been roughly linear, rather than exponential, inasmuch as the nine additions to global installed capacity each year from 2009 to 2017, although trending upward, have all been within 30 percent of 50,000 megawatts.

An important distinction exists between onshore and offshore wind installations. As of 2017, of the 540,000 megawatts of global installed wind power, only 19,000 megawatts (3.5 percent) were installed offshore. Almost two-thirds of offshore capacity was in the United Kingdom and Germany, with China in third place. Offshore wind's share is growing: it accounted for eight percent of new wind capacity installed in 2017 (4,300 out of 53,000 megawatts).

The waters off the East Coast of the U.S. are favorable to wind power because of steady winds, ocean depths that increase slowly with distance from shore, and close proximity to large electric loads in coastal cities. Only one U.S. offshore wind farm now operates, near Block Island, Rhode Island, with five six-megawatt turbines. However, a burst of new construction may lie immediately ahead in the northeastern U.S., as the wind industry responds to lower costs in combination with mandates from several states for specific amounts of offshore wind by specific dates. With such mandates, these states are competing for new, large wind farms off their coasts.

Wind Electricity Production, Globally and for the Leading Countries

The wind industry's primary sources provide data for installed capacity but do not estimate actual electricity production. However, the U.S. Department of Energy's Energy Information Agency, in its International Energy Outlook 2017, has such estimates for wind electricity production in 2015 for the world and for specific countries. Total global wind electricity production was 890 billion kilowatt-hours in 2015. China and the U.S. produced essentially the same amount of wind electricity that year, 240 billion kilowatt-hours each – or just over a quarter of the world's wind electricity in each country. Figure 4.3, from the Energy Information Agency, shows how global wind power production evolved from 1992 to 2015. It also disaggregates global production to show China, the U.S., and Germany separately. Offshore wind is also growing, from 2.6 percent of overall wind generation in 2011 to 4.4 percent in 2015.

The world is now producing about five percent of its electricity from wind. For Denmark, famously, wind accounts for 48 percent of its overall in-country electricity generation.[2] The corresponding values for Germany, the U.S., and China recently are 12 percent, 4 percent, and 3 percent, respectively.

[1]These must be only the large wind turbines. Another source (https://www.worldenergy.org/data/resources/resource/wind/) reports that there were 800,000 "small" turbines installed as of 2015, and that their combined capacity was less than 1,000 megawatts (only two tenths of a percent of total installed capacity). The average capacity of these small turbines, therefore, was roughly one kilowatt, more than one thousand times smaller than the average "large" turbine. Small wind turbines evidently play a negligible role in grid-scale electricity.

[2]In 2015, Denmark had net imports of 17.5 percent of its electricity supply, since it trades on the Nordpool market with countries like Germany, Norway, and Sweden [1]. In terms of consumption, wind met 42 percent of electricity demand.

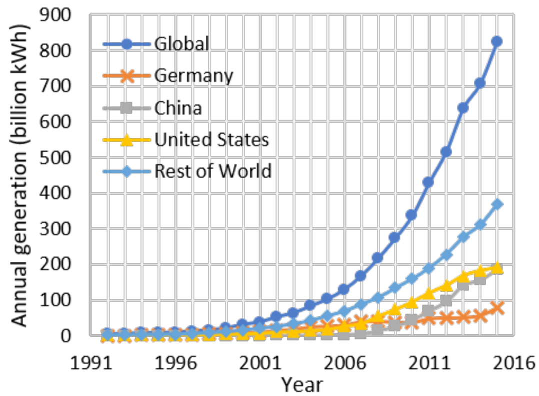


Figure 4.3: Annual global wind energy generation, and a disaggregation into four regions, 1992-2015. Data source: U.S. Energy Information Administration, https://www.eia.gov/beta/international/data/browser/.

As for wind generation per capita, the leading countries are all European: Denmark, Sweden, Ireland, Portugal, Spain, and then Germany. The U.S. ranks ninth and China twentieth.

We can combine the insights in Figures 4.1 and 4.3 using the concept of the capacity factor, which is a measure of onsite turbine performance. The capacity factor is the energy actually produced over a period of time divided by energy that would have been produced during that time if the turbine had produced electricity at its rated capacity.[3] The average capacity factor for the world's wind turbines was 22 percent in 2015. Because China produced roughly the same amount of electricity as the U.S., but from approximately twice as much installed capacity, the capacity factor for China's wind turbines was only half that for the U.S.: roughly 15 percent for China and 32 percent for the U.S. in 2015. The capacity factor for Chinese wind power is increasing as China better utilizes its generation capacity [2]. In fact, preliminary data shows the capacity factor has jumped above 21 percent in 2017.

Capacity factors are high where winds are steady, and turbines are sized to match the wind. Because offshore winds are generally steadier than onshore winds, offshore sites usually have higher capacity factors than onshore sites. As an example of how high a capacity factor can be with steady winds and good grid integration, the twelve offshore wind farms operating in Denmark in 2017 had an average capacity factor of 46 percent [3]. Winds are also less uneven further above the surface, so taller turbines lead to higher capacity factors as well.

Deployment by U.S. State

Figure 4.4 shows a breakdown of the installed wind capacity in the U.S. by state in 2016. Texas was responsible for nearly one quarter of installed capacity, followed by Iowa, Oklahoma, California, and Kansas. Not shown in Figure 4.4, leading in the percentage of in-state electricity generation coming from wind were Iowa, South Dakota, Kansas, and Oklahoma, all of which produced more than 25 percent from wind power. Texas ranked 11th, with 13 percent of its electricity generation coming from wind.

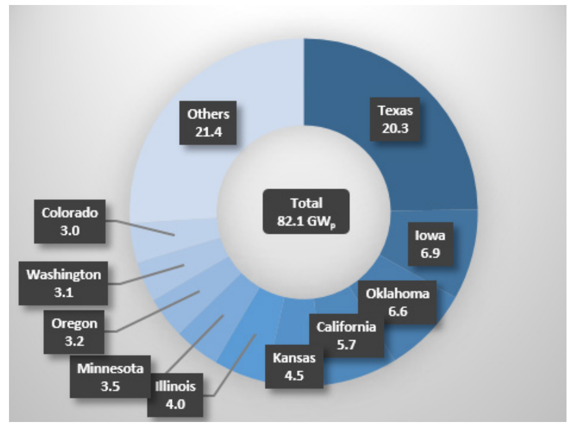


Figure 4.4: Cumulative installed wind capacity at the end of 2016 by U.S. state, in gigawatts of peak capacity (GWp). 1 gigawatt = 1,000 megawatts = 1,000,000 kilowatts. Data source: Department of Energy [4].

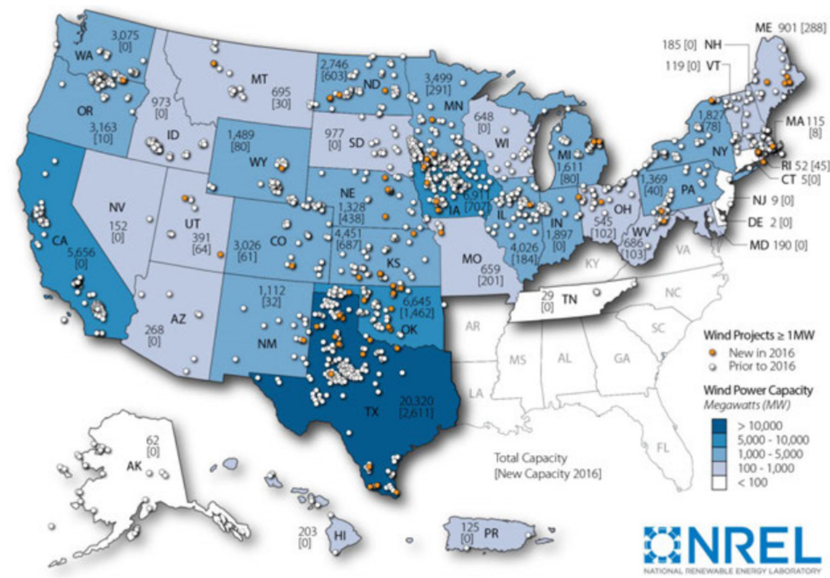
Figure 4.5 shows the geographical distribution of all U.S. wind projects larger than one megawatt operating by the end of 2016, and it specifically identifies those projects added in 2016. Comparing Figure 4.5 to the U.S. wind map in Figure 3.2 reveals, not surprisingly, that wind farms are concentrated where the wind resource is most abundant. The concentration of projects in western Texas, western Oklahoma, and Iowa is evident, as well as the absence of wind projects in the southeastern states. In 2015, there were almost 700 working wind farms in the U.S., with a combined capacity of 62,000 megawatts, making the average capacity of a U.S. wind farm 90 megawatts. The average capacity of the farms that were added in 2015 was 150 megawatts, an indication that farms are getting larger. As a historical footnote, in 1975 there was only one wind farm in the U.S., located in southern California.

4.2 Wind Energy Projects

When wind turbines are deployed whose rated capacity exceeds one megawatt, they rarely stand alone. Rather, many turbines are clustered, forming a wind farm.

A typical wind farm is planned, financed, and permitted as a single entity, and generally it hosts a single type of turbine. But some farms have a more complex history: the San Gorgonio Pass farm in California, for example,

[3] A turbine's rated capacity and its rated speed are design features that do not depend on where the turbine is sited. The rated speed is the speed above which the turbine is designed to produce roughly constant power, and the rated capacity is the power production at the rated speed. The rated speed and rated capacity are chosen by the wind power developer to maximize economic performance at a site.



Note: Numbers within states represent cumulative installed wind capacity and, in brackets, annual additions in 2016.

Figure 4.5: Wind farms in the U.S., including those built in 2016 (orange) and before 2016 (white). The individual states are colored by their total wind capacity. Source: Department of Energy [4].

had a total capacity of almost 200 megawatts in 1985, spread over almost 3,000 turbines built by multiple developers [5]. Turbines at that time had an average capacity of only 60 kilowatts. By 2008, development had continued and the farm collectively evolved to a capacity of 615 megawatts from 40 individual projects, still with only around 3,000 turbines [6]. While wind farms today are usually independent entities, the Gansu Wind Farm "megaproject" in Gansu Province, China, partially completed, is a concentration of wind farms that is intended to reach a total rated capacity of nearly 20,000 megawatts.

Trends in Deployed Turbines

Figure 4.6 shows trends in three key turbine parameters for new turbines installed in the U.S. from 1998 to 2016: rated capacity, height of the tower (approximately, "hub height"), and rotor diameter (approximately, twice the blade length). Nearly all rotor diameters in 2016 were between 100 and 120 meters in diameter, while in 2009 none exceeded 100 meters. Meanwhile, the height of the tower has hardly grown since 2006, when on average it was 80 meters. Having a longer blade on a similar tower contributes to the falling cost of wind power, inasmuch as the tower is expensive and a larger blade enables greater harvesting of the energy in the oncoming wind.

The data underlying Figure 4.6 also show that, since 2009, new turbines smaller than one and a half megawatts have been rare and the majority of turbines in 2016 had a capacity between two and three megawatts. These trends in rated capacity are generally comparable to those in other countries.[4] The average rated capacity in the EU in 2016 was 2.64 megawatts, compared to 2.15 megawatts in the U.S. Unlike the U.S., Europe has a strong presence in offshore wind: in 2016, the average new European offshore turbine had a capacity of 4.8 megawatts, a rotor diameter of 128 meters, and a height of 93 meters.[5]

Investment Costs

The capital cost of a large wind project is dominated by the wind turbines themselves. Currently, GE Energy (U.S.), Vestas (Denmark), and Siemens (Germany) have supplied 88 percent of U.S. installations [7]. Globally, the same three companies are the three leading manufacturers of turbines, when accounting for the recent merger of Siemens and Gamesa (Spain). Goldwind (China) and Enercon (Germany) are also major players [8].

Figure 4.7 shows trends in turbine price per unit of capacity, 1997-2017, as analyzed by the National Renewable Energy Laboratory (NREL). From 1997-2017, there was a significant variation in the turbine cost, but not an overall trend. The price increase from 2001 to 2008, NREL found, was associated with a weak U.S. dollar relative to foreign currencies and increases in material costs, particularly for steel. Moreover, labor

[4]For data on wind power in European countries, see https://community.ieawind.org/task26/dataviewer.

[5]See http://windmonitor.iee.fraunhofer.de/windmonitor_en/4_Offshore/2_technik/3_Anlagengroesse/ and https://windeurope.org/about-wind/statistics/offshore/european-offshore-wind-industry-key-trends-statistics-2017/.

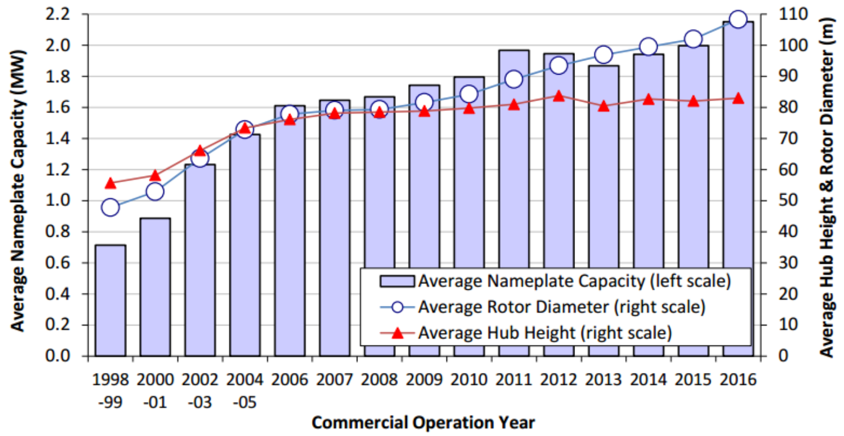


Figure 4.6: U.S. turbine capacity (blue bars), hub height (red triangles), and rotor diameter (white circles) by year installed. The "nameplate capacity" is the rated capacity; the rotor diameter is roughly twice the blade length, and the hub height is almost as large as the tower height. Source: Department of Energy [4].

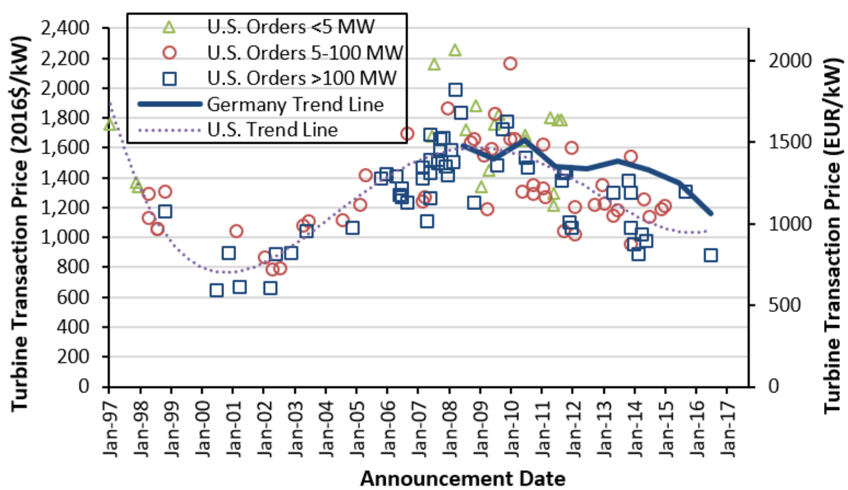


Figure 4.7: Wind turbine cost trends from 1997 to 2017, showing a rapid decrease in the late 1990s, increase until about 2009, and a decrease continuing until present. U.S. orders are broken into three size groups and also compared to trends for prices in Germany. "kW" is kilowatts. Source: Department of Energy (2017) [4] (modified for clarity) and International Energy Agency Wind, https://community.ieawind.org/task26/dataviewer.

costs, warranty costs, and profit margins rose over that period. From 2008 to 2015, the trends in foreign exchange rates and material costs reversed, driving overall prices back down. Figure 4.7 also shows that U.S. turbine prices were lower when purchases are bundled for larger wind farms, and that overall U.S. prices have been similar to other countries, such as Germany.

Figure 4.8 disaggregates the capital costs associated with the construction of typical onshore and offshore wind farms, considering all capital costs (more inclusive than just considering turbine costs as was presented in Figure 4.7). A reference 2.0 megawatt onshore turbine and a 4.1 megawatt offshore turbine are analyzed. For such an onshore project, the turbine cost accounts for 71 percent of total cost. The balance of system accounts for 20 percent, defined here to include all physical equipment on the farm other than the turbines, including electrical connections and turbine foundations, as well as construction and development costs. Financial expenses make up the remaining nine percent; these include "contingency," which allows for unexpected constructions costs.

For offshore wind projects, the total cost per kilowatt of capacity is much higher: $4,600 dollars per kilowatt, compared to $1,700 per kilowatt for onshore. The turbine cost (32 percent of the total capital cost) is less than the cost of the balance of system (47 percent). Siting fees, tower foundations, and assembly fees are all more costly offshore.

Since wind power costs are dominated by capital costs, the cost of capital is a critical variable, affected by access to credit, interest rates, and foreign exchange rates. In turn, access to capital is affected by funders' judgments about market structure, competitors, and risks. The financial viability of a wind power project improves when the turbine achieves a higher capacity factor, meaning that the same turbine now produces more kilowatt-hours of electricity over the same time period. To be sure, there are costs other than costs at the front end of the project: there are operating costs, such as the costs of maintaining and repairing the turbines, which, in turn, are related to turbine lifespan. And there are incentives and disincentives throughout the system resulting from government policies.

4.3 Some Features of the Wind Power Market

Producers of wind power sell their output through either "merchant" contracts or "power purchase agreements." These two arrangements differ in who bears the risks

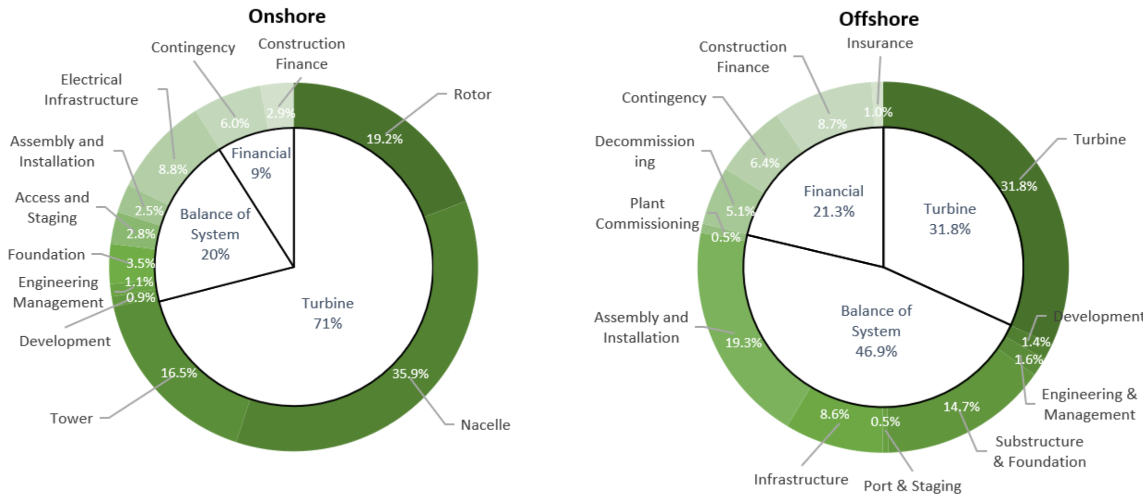


Figure 4.8: Breakdown of capital costs for typical onshore *(left)* and fixed-platform offshore *(right)* wind farms in the U.S. in 2015. Source: Mone et al. [7] (remade for clarity).

associated with uncertain future prices. Merchant wind power operators bear the risks themselves: they sell power on the real-time spot market or make only short-term contracts. Wind developers who have entered into a power purchase agreement have off-loaded the price risk to a buyer who agrees to pay a fixed price for a fixed number of years; the certainty of future revenue is often the key to securing project financing.

For wind farms the payout time for power purchase agreements is often 20 years (the nominal lifetime of a wind farm), but it ranges from less than 10 to as long as 30 years. The buyer is either a utility or (where an electricity market is deregulated) another credit-worthy customer, such as a large company that wants to increase its renewable energy consumption. Google and Amazon, among many others, have used this mechanism to acquire wind power in the last several years to reduce the carbon dioxide emissions associated with their operations [9].

The most important effect of wind power on electricity markets is to lower prices, at least where electricity markets have marginal-cost pricing (where the price at a given time is the cost of producing the last required kilowatt-hour at that time). When wind power is available, it is usually less expensive than the two energy sources that currently dominate most electricity markets — coal and natural gas. The extra cost of running a wind turbine on a given hour, versus not running it, is considerably less than the extra cost of running a plant burning coal or natural gas. The fossil fuel plant needs to pay for the cost of the extra fuel it burns, but a wind farm needs only to pay the salaries of the plant's operators and the costs associated with a slight shortening of the lifetime of its turbines by this extra use. As a result, when electricity demand exceeds wind supply, all the wind power available is usually sold. Less coal and gas power is sold as they become less profitable, and what is sold gets a lower price.

As wind power drives down the price of electricity, it necessarily affects the profitability of wind power itself. Figure 4.9 illustrates this phenomenon by showing how the electricity price is suppressed when renewable energy is abundant. Using weekly data for the German electricity grid in 2013, the grid's electricity price is plotted against the fraction of total grid electricity provided by wind and solar power. The average price during weeks when solar and wind power accounted for 15 percent of total electricity was one-third less than when they accounted for only 5 percent. Several proposals are being considered to address this form of self-limiting economics [10].

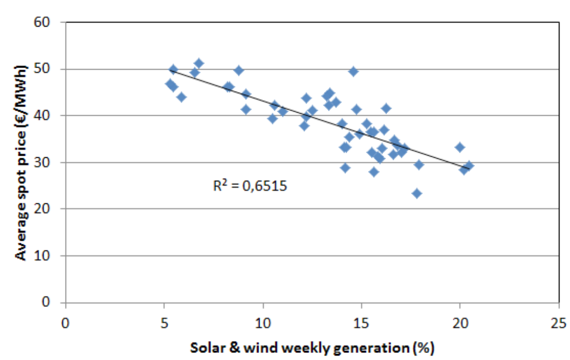


Figure 4.9: The relationship between weekly electricity prices in Germany in 2013 and the percent of that week's total electricity production provided by solar and wind power. On the vertical scale, the € is a euro, slightly more than a U.S. dollar. Source: The Energy Collective, http://www.theenergycollective.com/schalk-cloete/324836/effect-intermittent-renewables-electricity-prices-germany.

4.4 Policy Incentives for Wind Power

Federal Incentives in the U.S.

Incentives at all levels of government promote every type of energy generation. Each incentive lowers the costs of one source of supply relative to those sources with which it competes. In the case of wind, government policy has been crucial in creating a self-sufficient industry capable of competitive power generation.

The most widely used incentive for utility-scale wind projects in the U.S. has been the federal government's Production Tax Credit. The Production Tax Credit gives owners of wind farms a tax credit for every kilowatt-hour of electricity that the farm generates, for the first ten years of a farm's operation. In 2016 the Production Tax Credit was 2.4 cents per kilowatt-hour, but it is being phased out. It was reduced by 20 percent and 40 percent for projects that began in 2017 and 2018, respectively (and then corrected for inflation). The tax credit is scheduled to drop by 60 percent in 2019 and to disappear entirely beginning in 2020 [11].

The rules for the Production Tax Credit include a provision that encourages existing wind farms to repower. If at least 80 percent of the farm's capital cost is replaced with new equipment, then the farm can be eligible for another 10 years of benefits [12]. This can take the form of replacing older turbines with more modern equipment, while re-using existing sites and towers. The rules also contain a safe harbor clause, which assures that projects are considered "in construction" as soon as five percent of the replacement cost has been spent. Aware that the value of the Production Tax Credit would fall in 2017, several wind farm owners invested the necessary five percent by the end of 2016 to get the full 2016 credit; they now have the option to invest in the replacement, as long as they complete the replacement by 2020.

Two other federal incentives currently foster renewable energy in the U.S.: favorable depreciation deductions and the Investment Tax Credit. The federal government's tax depreciation rules for wind projects allow wind energy assets to be depreciated over five years, a much shorter period than the full project lifetime. Wind has also been eligible for special bonus depreciation, writing off 50 percent of the asset value within one year of project completion. The benefit from the Production Tax Credit and from accelerated depreciation rules can be significant, provided that there is a partner involved with sufficient tax liability [13, 14].

The Investment Tax Credit has not proved important to the wind industry. The Investment Tax Credit allows developers to deduct a portion of the cost of their investment from their tax liability, but it has been used mostly for small wind projects (projects with a total capacity of less than 100 kilowatts). It cannot be claimed if the Production Tax Credit is claimed, and the Production Tax Credit is usually more advantageous for a large wind project. As a general rule the Production Tax Credit is used for wind projects and the Investment Tax Credit for solar projects.

State Incentives in the U. S.

The principal state-level incentive for wind power in the U.S. is the Renewable Portfolio Standard, which mandates that retail electricity providers include a specified minimum fraction of their total electricity from renewable electricity; otherwise, they face penalties. More than half of the U.S. states currently have such targets [15]. In New Jersey, for example, each provider of electricity is required to supply 24.5 percent of its electricity from renewable sources in 2020. This requirement is implemented flexibly, through a market in Renewable Energy Certificates. Massachusetts has announced that it intends to procure up to 1,600 megawatts of offshore wind by 2027, and several other northeastern U.S. states are making similar decisions. Some states have already established a competitive bidding process, where the state will choose those developers offering to provide the requisite wind power at the lowest cost.

National Incentives Outside the U.S.

Many countries in the European Union, as well as China, promote wind power using an incentive called the feed-in tariff [16, 17, 18], where the government pays the producer of wind energy a specified amount for each kilowatt-hour of electricity produced. The feed-in tariff is similar to the Production Tax Credit in the U.S., but one important difference is that the ratepayers (electricity customers) pay the feed-in-tariff, while the taxpayer pays the Production Tax Credit.

Sometimes, the price of the feed-in tariff is established by a reverse auction in which governments award a project to the developer willing to accept the lowest payment. In Denmark, the Horns Rev 3 Project was won in 2016 by a developer who accepted a payment of approximately 11 U.S. cents per kilowatt-hour. This price was 32 percent lower than the previous auction's price for production from an offshore wind farm – but far higher than the prices in new contracts for wind power in the U.S. (as low as 3 cents per kilowatt hour).

Governments incentivize wind power indirectly when they create a price on carbon dioxide emissions to the atmosphere that applies to electricity production – either a tax or a cap-and-trade market. The objective of carbon pricing is to reduce the rate of onset of climate change and its associated societal costs. The incentive for wind power is relative to power from fossil fuels, because fossil fuels emit carbon dioxide when they are burned, but wind power has almost no associated emissions. The incentive has little effect on the competitiveness of wind power relative to solar power, hydropower, or nuclear power, because they all have similarly low carbon dioxide emissions.

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Article 5: The Single Wind Turbine: From the Wind to the Blades

In this article, we bring the reader along on a tour of an individual large modern wind turbine up close, introducing the key components that allow it to harness the wind's energy and convert it into mechanical energy. We begin by noting the size of the turbine and the layout of the wind farm in which it is located. We then explain why a turbine looks as it does today: why it has three blades, why the blades taper and twist, what limits how quickly the blades rotate, and how the blades generate power. We also tour the inside of the turbine, looking at the key components and control systems within the nacelle.

5.1 The Turbine's Blades and Tower

Visiting a wind farm is markedly different from visiting a solar farm. Each wind turbine stands tall, separated from its neighbors by several hundred meters or more. Surrounding each turbine is open space - often farmland with animals grazing or crops growing. In some cases other infrastructure (oil and gas wells, for example) shares the land. Figure 5.1 shows one such scene, although many are not as idyllic.

Figure 5.1: Wind turbines in a bucolic setting. Photo: Symbiot/shutterstock.com, https://www.shutterstock.com/video/clip-10171613-stock-footage-summer-countryside-with-wind-turbines-and-agricultural-field-with-grazing-cows-full-hd-p.html.

As you approach an individual wind turbine, its enormity becomes apparent. You realize that the blades and tower must bear the force of the wind pushing them backwards, and they must be very strong to resist this force. For specificity, we assume the rated power of the turbine is three megawatts, which is a typical value for the large turbines sited on land recently. (Offshore turbines are generally larger.) The tower stands 80 meters tall, and that's not including the blades, which make it taller still. It is an upright, cylindrical structure, several meters in diameter, tapering as its height increases. The tower rests on a large concrete foundation.

This is the most common modern tower. It is assembled onsite from a few tubular sections. The towers supporting some older wind turbines have a steel lattice-work structure that requires extensive on-site construction. Some newer towers are beginning to be constructed from concrete, either assembled onsite from modular sections or even cast onsite.

A pod, known as a nacelle, is sitting on top of the tower. At the front of the nacelle is a hub, which is where the blades meet and connect. Together, the hub and blades make up the rotor, so called because it rotates as the wind blows. As with all of the other components in front of you, the blades are enormous too. Each blade is 50 meters long, so the total rotor diameter reaches 100 meters. Looking up at the turbine, you see that there are three blades. The choice of three blades is a signature example of the trade-off between efficiency and cost. A wind turbine's sole purpose is to convert wind energy into electrical energy. To do this effectively, it must capture as much energy as possible from the incoming wind. Having more blades allows the turbine to "sweep" more air per revolution, providing the potential to capture more of the incoming wind energy, but at the expense of increased weight, complexity, and cost.

To reduce costs, a turbine could use fewer blades, perhaps only two. To generate the same amount of energy as a higher number of blades, two blades would need to sweep through the air more quickly. However, other issues arise. The noise and vibrations originating from the blades could quickly exceed acceptable limits, as the blade tip is traveling too quickly. The structural strength of the blade becomes one concern and noise becomes another. Therefore, the rotation speed needs to be limited, which in turn reduces the energy production efficiency. The result is a lower cost turbine, but also one that produces less power. On balance, the power penalty makes the two-blade design more expensive.

In the middle lies the Goldilocks compromise: the ideal balance that maximizes the ratio of energy extracted to cost. Across the wind industry, this compromise is now settled at three blades.

A Damaged Blade is on the Ground

Land is so cheap at this Texas wind farm that a blade that had to be removed because it was damaged was not trucked away but was left resting on a mount on the site, so you can see it up close (see Figure 5.2). What an opportunity to look closely at the blade's shape.

Figure 5.2: A 50-meter blade stored at ground level, being examined by one of the authors (Greg Davies) at the Sherbino 2 wind farm in western Texas. The blade is viewed from its root, looking toward its tip; it is thicker at its base, twisted, and tapered. Photo: Ryan Edwards.

You see that the blade, in cross-section, has a similar shape to an airplane wing (the shape is called an airfoil). You note that the blade is thick for about the inner third of its length and then tapers down gradually to a smaller size at the tip. You are surprised to see that the blade is twisted along its length: the blade's front edge (called the leading edge, since it contacts the wind first) points in a different direction depending on whether you are looking at the blade root, which is the base of the blade near the hub, or the blade tip, or somewhere in between. Let's understand these three features of the blade one at a time.

Why does a blade have a cross-section like an airplane wing?

A great deal of design effort ensures the turbine blade is shaped so that the energy in the wind is harvested efficiently. A cross-section through the blade reveals that it has a shape called an airfoil (see Figure 5.3). In many respects, a turbine blade is similar to an aircraft wing, except that instead of incoming air producing a lift force that pushes an aircraft upwards, the incoming air creates a lift force that rotates the blades, hub, and shaft. In doing so, the blades extract kinetic energy from the wind and transform it into rotational kinetic energy, which is then harnessed in the turbine's mechanical and electrical systems to generate electricity.

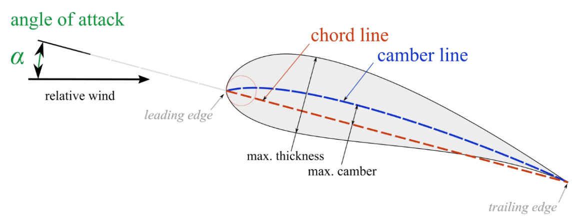

Figure 5.3: Features of an airfoil of both a wind turbine blade and an airplane wing. Source: Olivier Cleynen, https://commons.wikimedia.org/wiki/File:Wing_profile_nomenclature.svg.

The rounded front edge of the blade is the leading edge and the sharper rear edge is the trailing edge. The incoming airflow comes into the leading edge, and the outgoing air leaves from the trailing edge. The chord of the airfoil is the straight line joining the leading and trailing edges. The camber line is a curved line that lies midway between the upper and lower surfaces of the airfoil and tells us how asymmetric or curved the airfoil is.

The orientation of the airfoil with respect to the incoming wind determines how effectively lift is produced. It is quantified by the "angle of attack," which is the angle between the chord line and the incoming airflow (see Figure 5.3). A symmetrically shaped airfoil will produce no lift at a zero angle of attack; however, an airfoil with camber will produce lift even at zero angle of attack, due to the asymmetry in its shape. As the airfoil angle of attack is increased, the lift force increases approximately linearly, up to a certain angle. Tilt too far, and the amount of lift will drop dramatically. This is called stall, and it occurs when the air flowing around the airfoil is no longer hugging the airfoil surface closely but begins to separate from the airfoil.

Why are the blades tapered toward the tip?

Two reasons: first, the taper equalizes the energy generation along the entire blade. If a blade were not tapered but rather had the same chord length from the hub to the tip, more energy would be extracted from the wind at the tip than at the root, and the result (not obvious) would be a reduction in the total rotational energy produced by the same incoming wind. Second, the taper reduces the bending of the blade by reducing the wind forces near the tip. A larger force on the tip would create structural requirements to carry that force all the way to the root, so the taper helps to avoid excessive blade bending, fatigue, and failure.

Why are the blades twisted?

An oversimplified answer is that the blades are twisted because when the blades are spinning, the air hits the tip of a blade and the base of the blade from very different directions. This is because the blade tip is traveling far faster than the blade root.

Imagine that you're strapped to the tip of the rotating blade, with your face pointing in the direction of rotation. From which direction does the wind appear to be coming? As the velocity of the blade tip is much faster than the incoming wind, the apparent wind (known as the relative wind) is moving almost directly toward your face, and only a small component of the wind velocity is hitting your face from the side. For a tip speed ratio of 6, the angle of the relative wind into your face is about 10 degrees. The relative wind direction is almost entirely in the plane of the rotating blade, and hardly matches the direction of the distant incoming wind at all. Said another way, the wind is coming at you from a completely different direction than if you were standing stationary in front of the turbine. Thus, not only is the relative wind speed much greater at the tip, but it also has a different direction than the relative wind direction near the blade root.

Each airfoil section of the turbine blade must have a small angle of attack with respect to the relative wind velocity. At the tip of the blade, where the relative wind velocity is almost completely in the plane of the blades, the leading edge of the blade must point almost in the direction of rotation. Close to the root of the blade, where the relative wind velocity is coming largely from the wind direction, the leading edge of the blade must point nearly into the incoming wind. In short, the blade must twist. The optimal angle of attack for each section of the blade takes into account drag forces as well, which oppose the motion of the blades much like drag acting on a car. There is typically an optimal angle of attack that maximizes the ratio of the lift force to the drag force.

Compromises involving aerodynamics, structural forces, materials, and costs

The details of the shape of a blade are the outcome of a balancing of the needs for adequate structural strength and the need for aerodynamically efficient power generation, all the while taking into account the limitations of the materials from which the blades can be made and minimizing the total cost. In turn, the cost incorporates issues of safety, longevity, and maintainability. The outcome of this optimization, oversimplifying, is a design of the inner third of the blade (which carries almost the entire blade load) that is dominated by structural considerations, resulting in a thick airfoil shape. In contrast, the optimized design of the outer third of the blade, where almost all of the turbine power is generated, is driven by aerodynamics. The shape tapers significantly to optimize the distribution of the loads along the length of the blade and prevent a concentration of forces at the tip. The middle third is where the trade-off of aerodynamics and structure allows for a variety of solutions.

The components of a wind turbine must be able to withstand immense stresses over their design lifetime, which is at least 20 years. A particularly important stress is the "fatigue load" that results from the blades moving through turbulent air, where the local angles of attack, and therefore the loads, are constantly changing. A second stress is the cyclic gravitational load, which is the force that opposes the blade's rotation when the blade is ascending and augments the blade's rotation when it is descending; the weight of the blade is important here. A turbine blade may go through forty million rotations over its lifetime.[1]

The Turbine Blades are Spinning

The blades on the turbine in front of you are spinning. You hold an anemometer up, a tool that is used to determine wind speed, and measure the wind high above you blowing at a steady but moderate speed of 9 meters per second (about 20 miles per hour). You count the amount of time it takes for a blade to complete a full revolution: about six seconds. Therefore, the rotor spins at 10 revolutions per minute (rpm). You notice that the tip of the blade is moving much more quickly than the section near the root, as it has to travel the full circumference of the rotor with each revolution. On this 50 meter blade, the tip is traveling at 52 meters per second, or 120 miles per hour. This is much faster than the speed of the incoming wind. The ratio of the tip

[1]Authors' estimate: A typical rotational speed for a wind turbine producing electricity at its maximum rate is six seconds per rotation; a blade rotating at that speed will complete five million rotations each year. Because much of the time the wind is not strong enough to produce maximum power (and sometimes not strong enough to produce any power), the number of rotations of the blades in a year is considerably lower, perhaps two million rotations per year, in which case in twenty years the blades will experience forty million gravitational load cycles.

speed to the speed of the incoming wind is called the tip speed ratio; it is about 6 in this case (52 meters per second divided by 9 meters per second is about 6).

This is an important observation for large, modern wind turbines. Even with the rotor spinning relatively slowly, the tips of the blades are still traveling very quickly, due to their sheer length. What does it mean for the design of a turbine that the tip speed is much higher than the incoming wind speed? First, to maintain noise within strict regulatory limits, the tip of the blade must travel below a maximum speed, typically about 80 meters per second. This is one reason modern turbines with long blades turn slowly - increasing the blade length means the rotation speed must decrease accordingly. For the largest turbines, with blades around 80 meters in length, typical rotation speeds might not exceed 10 rpm.

You Walk Halfway Around the Turbine

Turbine efficiency

With the wind still blowing hard, you now walk from the front of the turbine around to the rear and stand behind the turbine. You hold up your anemometer again and see that the wind is still blowing quite strongly. However, it is blowing less strongly than in the front. You conclude that some of the energy in the incoming wind has been extracted by the turbine, but not all of it.

In fact, it is impossible for a wind turbine to convert all the wind energy that hits the blades into electrical energy. The slower the speed of the wind behind the turbine, the more energy the turbine has extracted from the incoming wind. However, with quite general assumptions, there is a limit on the maximum amount of energy that a wind turbine can extract from the wind, known as the Betz limit. At the Betz limit, a turbine has an efficiency of 59 percent. (In more technical language, at the Betz limit the electric energy output is 59 percent of the kinetic energy in an incoming wind that, if the blades were not turning, would strike a disk of equivalent size to the swept area of the turbine blades.) At the Betz limit, it turns out, the air downwind of the turbine has slowed down to exactly one-third of the wind speed far upwind of the turbine. (At the turbine itself, at the Betz limit, the wind speed has dropped to two-thirds of the upstream wind speed). So, the wind speed behind a real turbine must be more than one-third of the speed of the incoming wind.

To gain some insight into why an optimal turbine efficiency exists, it is helpful to consider two limiting cases: no slowing down of the wind, and complete slowing down of the wind. At one limit, if the incoming wind travels straight past the turbine without slowing at all, the wind won't be losing any energy, and therefore the turbine cannot be producing any energy. Clearly the turbine needs to slow the wind in order to extract some energy from it. At the other limit, if the turbine brings the air to a complete standstill, then no wind would pass through the turbine (think of it like a grid-locked highway). With no wind traveling through the turbine, it would produce no energy, as before.

In between lies the optimum: the turbine must slow the air in order to extract energy from the wind, but there must still be sufficient wind speed behind the turbine to allow the "used" wind to escape and make room for a continual flow of "new," energetic wind through the turbine. With careful design it turns out that modern wind turbines are able to get close to the Betz limit: typical efficiencies range from 40 to 50 percent – that is, from 70 to 85 percent of the ideal Betz efficiency.

An enormous amount of wind energy influences the turbine. For our three-megawatt turbine in a nine meter per second wind, almost 90 metric tons of air flow past the turbine every second, from which roughly half of the kinetic energy is extracted and converted to electricity.

Wakes

Still standing behind the turbine, turn your back to the turbine and imagine the air going downwind. Air that flowed around the turbine is mixing with the air exiting from the turbine blades, creating a "wake." The mixing helps restore the speed of the wind behind the turbine – more completely as the distance downwind increases – until eventually the wind recovers its initial strength. You notice a second wind turbine in the distance; if it is close enough, the wake has lowered its output, compared to what that turbine would have produced from unaltered wind. When the wind farm was laid out, this negative wake-turbine effect was taken into account and the spacing between the turbines was made large enough to minimize losses. Indeed, the wake-turbine effect can limit the number of turbines that are sited on a wind farm.

The Wind Speed is Varying

You return to the front of the turbine and watch how the turbine performs as the wind speed varies. You get out your anemometer again. The wind has died down, all the way to zero, and the blades are not spinning. But then the wind slowly picks up, increasing to 1, then 2 meters per second, but the turbine blades are still not spinning. However, as the wind speed increases slightly more, to 3 meters per second, the blades change their orientation to the incoming wind (their pitch), and the turbine slowly begins to spin up. The speed where the blades first start to rotate is called the "cut-in" wind speed; it is the minimum wind speed at which a turbine has been designed to produce power.

The wind speed continues to increase, and you see that the rotational speed of the blades is also increasing, approximately in proportion to the increase in wind speed. As the wind speed increases, the turbine produces more and more power. You notice that, compared to the fully stopped position, the leading edge of the blades points more towards their plane of rotation and less straight toward the oncoming wind. The pitch of the blades is being adjusted by its control system to provide a near-optimal angle of attack for the incoming air.

The wind now is really blowing: its speed has reached 12 meters per second (27 miles per hour) and is climbing higher. You notice that once the wind speed exceeds 12 meters per second, the blades turn no faster than at 12 meters per second. Their rotation speed is about 16 rpm. The turbine has reached its power limit (the "rated" power). You notice, however, that the blades continue to change their pitch as the wind speed increases. This pitching keeps the power output constant, by reducing the angle of attack, and therefore the lift force, on the blades.

Finally, as you brace yourself against the wind, its speed reaches 25 meters per second (56 miles per hour). The blades change their pitch until the leading edge of each blade is pointing directly into the oncoming wind, and the turbine comes to a standstill. The turbine's "cut-out" speed has been reached, above which a turbine control system shuts the turbine down to assure that it is not damaged in sustained high winds.

The turbine's power curve and the wind speed

All this information is summarized in the "power curve" for a wind turbine. An idealized but representative power curve for a turbine is shown in Figure 5.4, left panel. It shows the cut-in speed, the rapid increase in output power between the cut-in speed and the rated speed, the plateau in output from the rated speed to the cut-out speed, and the fall of output power to zero above the cut-out speed.

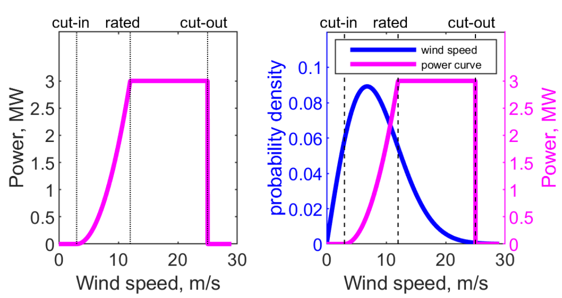

Figure 5.4: *Left:* An idealized power curve for a wind turbine. *Right:* The same power curve is superimposed on a representative wind-speed distribution.

You might wonder what fraction of the turbine's total energy production over a year is produced at wind speeds between the speeds for cut-in and rated power, and what fraction at wind speeds between the rated speed and the cut-out speed. The right panel of Figure 5.4 superimposes the wind probability at a particular site (blue curve) onto the turbine's power curve (pink curve, identical to the curve in the left panel). The relative positions of the two curves are typical: the site's most common wind speed (peak of the blue curve) is lower than the turbine's rated speed. Most of the time, the speed of the wind at the site is between the turbine's cut-in and rated wind speeds.

Some of the energy in the winds that blow faster than the turbine's rated speed (the wind speeds to the right of the dashed vertical line at 12 meters per second) is thrown away. That is the meaning of the fact that the turbine's power curve stops rising at its rated velocity. The choice of the turbine's rated speed for a given site is a compromise. Consider choosing a lower rated speed for the same site. In Figure 5.4, right panel, this would mean squeezing the turbine's power curve toward the left (perhaps, squeezing it so much that the rated speed coincides with the maximum of the wind-speed distribution). Such a "derated" turbine would be smaller and less expensive, but now more of the turbine's energy would be produced from winds above the rated speed, inefficiently. On the other hand, choosing a higher rated speed would result in a more expensive turbine producing only a limited amount of additional electricity from the high winds.

Figure 5.5 shows the electricity generated at various wind speeds for a specific turbine. This is a three-megawatt wind turbine, located in Colorado. In both panels, the leftmost bar represents the turbine not producing any power, and the rightmost bar represents the turbine producing at its full rated power, three megawatts. The ten bars in between represent the wind power grouped into power increments of three-tenths of a megawatt: i.e. 0 - 0.3, 0.3 - 0.6, and so on.

The left panel shows the fraction of time that this wind turbine generated various levels of power. Much of the time very little power is produced; for example, the first bar tells us that almost 10 percent of the time no power is produced at all, and the second bar tells us that just over 20 percent of the time the turbine is producing between zero and three tenths of a megawatt. Combining the first four bars, almost half the time the turbine is producing at less than one third of its maximum output power. From right-most bar, we learn that the turbine produces its full three megawatts of output power 20 percent of the time. This is the power generated when the wind speed is greater than the rated speed – in this case, 12 meters per second. The right panel conveys the same information in a different way. It shows the fraction of the total energy produced by the turbine, for the same wind speeds as in the left panel. Very little of the turbine's total energy production is at low wind speeds. Almost half of the total output of the turbine occurs when the turbine is operating at three megawatts, its rated power, even though (left panel) the turbine operates at its rated power only 20 percent of the time.

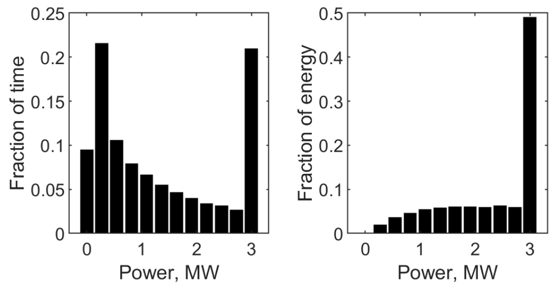

Figure 5.5: ***Left:*** **The fraction of the time that a three-megawatt turbine produced power at various narrow ranges of rates, in megawatts (MW).** ***Right:*** **The fraction of the total power that the same turbine produced at these same rates. In both cases the first and twelfth bars show the fractions for no power at all and for full power, respectively. The ten intermediate bars show intervals of three tenths of a megawatt.**

The Wind Twists and Turns. So the Turbine Moves like an Owl's Head.

While you are observing the wind turbine, the wind direction changes several times. You notice that the nacelle pivots on the tower so that the plane of the blades always faces the wind. This movement of the entire nacelle and blades is called yaw motion, and it is accomplished by yaw motors in the nacelle. If it were not for this adjustment to track the wind direction, the incoming wind would strike the turbine at an angle, and the turbine power output would drop.

Tracking the wind direction is an important form of wind turbine control. Turbines have a small weather station mounted on top of the nacelle, with an anemometer to measure wind speed and a wind vane to measure wind direction. These data are fed to a turbine-control system that engages a yaw motor to rotate the nacelle into the wind. Thus, the performance of the wind turbine is critically dependent on the wind vane.

The turbine cannot track the wind direction instantaneously, because the nacelle is heavy and the rotor has large loads acting on it. Instead, the yaw control system moves slowly. If the wind direction fluctuates rapidly, the wind turbine designer does not want the nacelle to chase after every change in the wind direction – to move toward the east from the north for ten seconds, for example, and then immediately back toward north. The majority of turbines have a very simple control strategy: only after the wind direction (or heading) has deviated by two to four degrees will the turbine yaw to the new wind heading. This assures that the turbine is always oriented nearly optimally, while avoiding too frequent excursions. With this control strategy, the losses from misalignment can be kept below one percent.

5.2 Inside the Tower

The person in charge of maintaining the wind turbine joins you and invites you to head into the tower to see what's inside. You enter the tower through a small door. Immediately you realize that the tower is a hollow steel shell. At the entrance level, the tower floor is crowded with electronic equipment, evidence that wind turbines have become "smart" devices that integrate the signals from dozens of sensors to lower overall costs. Some controllers adjust the rotational speed and the pitch of the blades to assure optimal aerodynamic efficiency. Other controllers minimize the accelerations and decelerations of the blades and the mechanical vibration of the blades, gearbox, and towers produced, for example, by gusts of wind.

You look upward and notice vertical ladders ascending the structure, with intermediate platforms located periodically at various heights. There is also a service elevator that lets you travel from the bottom to the top of the structure. It can carry personnel as well as smaller parts and tools for turbine servicing and repairs. You see a significant amount of wiring routed down the tower. These wires carry the power generated up in the nacelle, as well as control signals and information, to the tower base. The power is then fed into a collection system that gathers power from the whole farm.

You ride the service elevator up almost 80 meters and then climb the final section on a ladder into the nacelle. The nacelle is large, about the size of a school bus. You are able to walk around on narrow platforms, although the space is filled with a lot of equipment and is very tight. Particularly prominent are electric power generators and also the yaw motors that move the entire nacelle on a large ring gear. The layout of the equipment in Figure 5.6 is typical of what you might see.

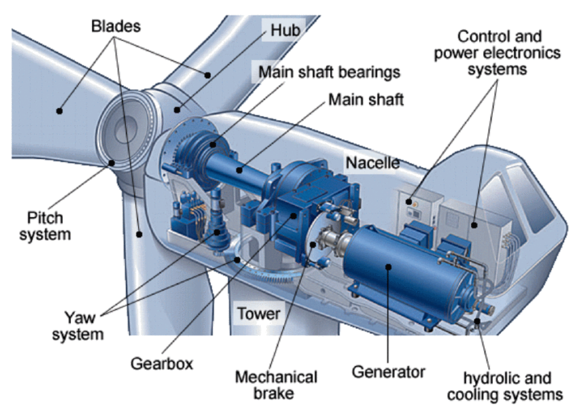

Figure 5.6: A typical layout of equipment inside the nacelle of a modern wind turbine. Source: Tchakoua et al., https://ieeexplore.ieee.org/abstract/document/6618706.

Inside the nacelle it is quite noisy, with air flowing rapidly even though, to keep you safe, your host stopped the turbine before you entered the tower. Towards the back of the nacelle, fans are drawing outside air through a heat exchanger to cool the various electronic and hydraulic systems. Beneath the coolers are the transformer and some power electronics. Moving forward, the next large piece of equipment is the generator that converts the energy in its rotating shaft into electrical energy. The shaft of the generator is connected to a gearbox, which changes the slow rotational speed of the blades into the much higher rotational speed of the generator shaft. Directly in front of the gearbox is the slowly rotating hub to which the blades are attached.

Also within the nacelle is a hydraulic power unit that provides the power to drive the turbine control systems – the yaw motors that head the turbine into the wind control and the motors that control the pitch of the blade (the angle between the blade and the incoming wind). You can see the large bearings at the root of the blades, which change the pitch. Some turbines use electrically driven systems instead of hydraulic systems.

5.3 Back at the Blade on the Ground

You are not able to see inside the blades from the nacelle, but now you have new questions about the blade, so you descend to ground level, go outside, and revisit the spare turbine blade resting on a mount (recall Figure 5.2). Down the surface of the blade, you see small metal fasteners attached periodically to a conductive pathway that extends through the blade all the way back to the hub and eventually to the nacelle. This is a protection system in the event that a turbine blade is struck by lightning, a risk for any large object standing in a wide open space. Damage to a turbine blade from a lightning strike can result in a costly repair.

Standing at the root of the blade, you note that the diameter is so large that you could stand upright inside. You can look inside, down the length of the blade, because it is open at the root (see Figure 5.7, top panel). You see a hollow construction with two spars, called shear webs, which connect the top and bottom surfaces of the blade. These make a three-compartment structure, which is very strong and lightweight.

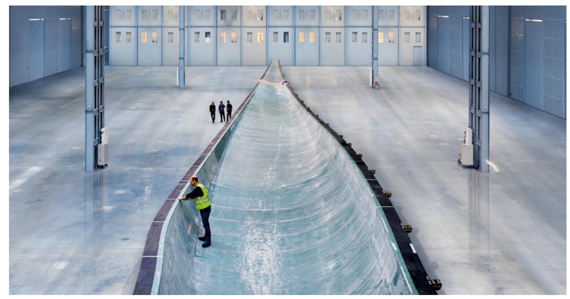

Figure 5.7: ***Top:*** **Looking inside a turbine blade (the BP Sherbino Mesa II turbine blade) at its two shear webs and its balsa/fiberglass construction. Photo: Greg Davies.** ***Bottom:*** **A facility for the fabrication of turbine blades, showing the mold for a half-blade. Photo: Siemens AG, Munich/Berlin, https://www.siemens.com/press/en/presspicture/?press=/en/presspicture/pictures-photonews/2012/pn201204.php.**

The choice of materials for the blade may surprise you: it is a mixture of balsa wood and resin-impregnated fiberglass. (Some large modern blades also incorporate carbon fibers, although this adds to cost.) These materials are preferred over steel and aluminum because of their lighter weight, because they can be shaped into complex forms at less cost, and because they are better at withstanding fatigue. Figure 5.7, bottom panel, shows a typical fabrication facility for turbine blades. Two halves are made separately, and each half is fabricated as a single piece from root to tip. The manufacturing method enables the combination of complex aerodynamic shape and blade strength.

Your tour is over.

Article 6: The Single Wind Turbine: From the Blades to the Grid

Article 6 starts where Article 5 ends. Article 5 explains the conversion of wind energy into the energy in rotating blades turning a shaft. It involves the visible story – the front office. Article 6 completes the story that results in grid-suitable electricity. Mostly, the components in Article 6 are inside the wind turbine's nacelle; they are the back office. The back office is evolving. Some turbines now dispense with the gearbox, produce power at a wider range of wind speeds, and feature longer lasting, lighter, and smaller components.

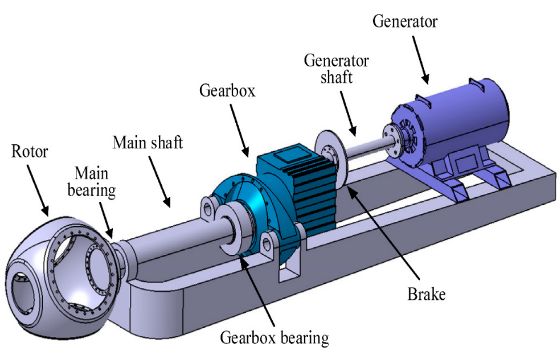

Figure 6.2: The wind turbine gearbox, which couples the main shaft and the generator shaft. Source: Qian, Ma, Zhang, https://www.mdpi.com/1996-1073/10/10/1583/xml.

6.1 The Wind Turbine Electro-Mechanical System

After the turbine blades have converted the energy in the wind into the rotational motion of the main shaft, there are two further steps before electricity can be placed on the grid. First, the rotational energy in the main shaft is transformed into electricity by a gearbox and a generator. Second, the characteristics of the electricity are manipulated to become compatible with the strict requirements of the electrical grid.

Figure 6.1 shows a block diagram of the mechanical and electrical components of a wind-turbine's energy-conversion system, from the blades to the grid. Figure 6.2 shows the physical layout of a portion of Figure 6.1: the rotor, the gearbox, and the generator. The "rotor" in both Figure 6.1 and Figure 6.2 refers to the blades and hub, which turn a rotating shaft. A different "rotor" is the portion of the generator that rotates; in this distillate, we will call it the "generator rotor."

The remaining three sections of this article address the three main components: the gearbox, the generator, and the transformer.

6.2 The Gearbox

The shaft of a wind turbine that rotates with the heavy blades and hub is spinning much too slowly for a conventional generator to produce power efficiently. A

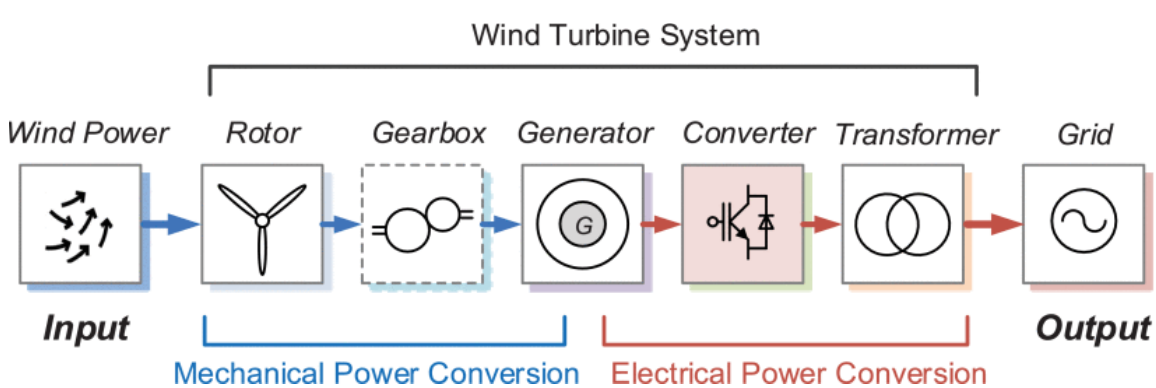

Figure 6.1: Block diagram of a wind turbine system. Source [1].

gearbox is used, conventionally, to connect that shaft to a second shaft and to spin the second shaft at a much higher rotational speed. The fast-spinning shaft rotates inside the generator and produces electricity.

For megawatt-level wind turbines, a typical rotation rate for the blades is 10 revolutions per minute (rpm) or, equivalently, six seconds for a complete rotation of the blades. The turbine completes 1/6 of a cycle per second. The electric grid operates on alternating current (AC) with oscillations at a constant frequency that is hundreds of times higher: depending on the country the frequency is either 50 cycles per second (3,000 rpm) or 60 cycles per second (3,600 rpm).

A gearbox typically uses gears in three stages to achieve this high multiplication of the rotational frequency from the slow-turning shaft to the fast-turning shaft. Figure 6.3 shows such a three-stage gearbox, with a low-speed stage, an intermediate stage, and a high-speed stage.

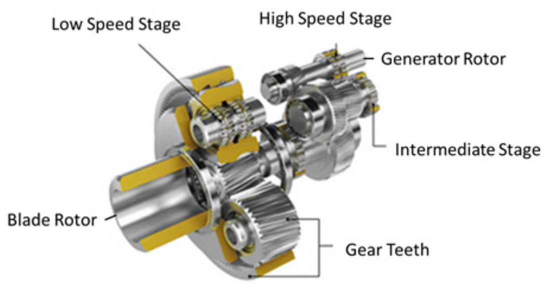

Figure 6.3: A representative three-stage gearbox. Source: Olympus, https://www.olympus-ims.com/it/applications/rvi-wind-turbine/.

The gearbox occupies 5 to 15 percent of the nacelle volume, weighs several tons, and contributes 20 to 30 percent of the turbine cost [2]. No gear system is 100 percent efficient: as a rule of thumb, roughly one percent of the power is lost at each gear stage. Thus, a 500 kilowatt three-stage gearbox running at full capacity dissipates energy at a rate of about 15 kilowatts. This heat is removed by a cooling system.

Much effort in the wind industry has been directed toward reducing the costs associated with the gearbox. The source of the high costs is the relatively short lifetime of the gearbox and its need for regular maintenance. Even with regular inspection and maintenance gearboxes often failed within an operating period of five years, while the typical target lifetime of a utility-scale wind turbine is twenty years. The lifetime of the gearbox is limited by mechanical stresses that originate in events like the random gusting of the wind that bends and twists the shaft and misaligns the gear teeth, producing uneven wear and degradation. Technical advances in many areas are extending the lifetime of the gearbox and reducing its maintenance costs: new materials, heat treatment, lubricants, and innovative mechanical structures, all of them coupled to improved power electronics and automatic control.

6.3 The Generator

The modern generator makes heavy use of advanced power electronics to produce constant-frequency electricity at the frequency required by the grid (60 cycles per second in the U.S., 50 cycles per second in much of the rest of the world). The generator has a stator and a rotor. The stator is a fixed structure mounted on a supporting base, and the generator rotor spins within or outside the stator. As the generator rotor spins, it creates a rotating magnetic field, which causes currents to flow within the stator, generating electricity that can be fed into the electric grid. Energy is transferred from the generator rotor to the stator through electromagnetic coupling. Today's large wind generators weigh from 10 to 50 tons.

Two broad classes of turbines dominate the wind industry, differing in the way they transform the slow rotation of the blades and hub into the fast rotation of the generator rotor. The first class achieves the required frequency multiplication with a gearbox, as just discussed, that couples the rotating blades and hub to a kind of "high-speed" generator widely used in other applications. The second class dispenses with the gearbox in favor of the "direct-drive" generator, where the same shaft that turns with the blades also turns the generator's rotor at the same low speed (again, think, 10 rpm); the direct-drive generator is also called a "low-speed" generator. The gearbox is shown as a box with dashed boundaries in Figure 6.1 to represent the possibility that the gearbox may not be present.

How does the direct-drive generator achieve the frequencies required by the grid without two shafts and a gearbox that connects them? It does so by placing a large number of pairs of magnets on the rotor or the stator of the generator, so that one turn of the rotor creates an electromagnetic excitation of every pair,

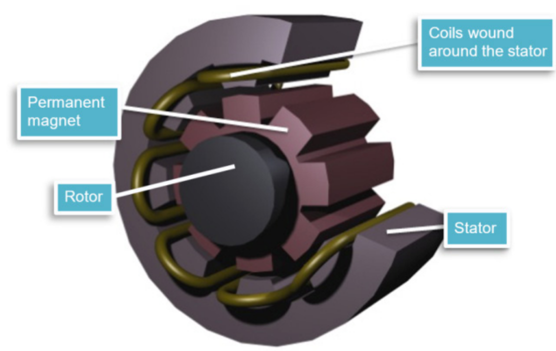

Figure 6.4: Key components of a direct-drive permanent magnet generator. Multiple pairs of permanent magnets perform frequency multiplication, instead of gears. Source: COMSOL, https://www.comsol.com/blogs/simulating-permanent-magnet-generators/.

boosting the frequency to a value close to what the grid requires. Then, the converter uses power electronics to get the exact required voltage [3].

The magnetic pairs are usually permanent magnets. See Figure 6.4 for a schematic of a direct-drive generator and Figure 6.5 for a photograph showing permanent magnets being placed inside the stator at a General Electric facility. The diameter of the “direct-drive” generator can exceed ten meters.

Figure 6.5: The manufacture of a permanent magnet generator. The permanent magnets are the silver brick-shaped objects, arrayed end-to-end along the inner perimeter of the stator; the left hand of the operator standing inside the stator is nearly touching one. Photo: General Electric, https://www.ge.com/reports/where-ge-makes-haliade-turbines/.

Both kinds of turbines are improving and dividing the market. The direct-drive generator avoids the costs associated with the gearbox (discussed above) and has fewer parts. But it is larger, and the technology is newer [4]. Its first costs are generally higher, but its maintenance costs are lower. As a result, the direct-drive generator is more competitive for offshore wind farms, where maintenance offshore is particularly costly. The generator rotor shown in Figure 6.5 is a part of a generator for an offshore wind farm. But, both onshore and offshore, developers of new farms are currently making both choices: either high-speed generators or direct-drive generators.

The dichotomy above, where there are just two turbine concepts, is an oversimplification. There are hybrid versions, “medium-speed” generators, which use a gearbox for some of the frequency multiplication and direct-drive for the rest. The high-speed stage of the gearbox is eliminated (which is the most difficult stage to make durable), and fewer permanent magnets are required for the direct-drive.

6.4 The Transformer

The electricity produced by the generator is not immediately suitable for the electricity grid, even though its frequency is now matched to the grid frequency. The voltage leaving the generator is much too low, usually around 600 to 1,000 volts, while the voltage of the distribution lines on the grid, which the wind turbine output must match, is typically 68,000 volts or higher. The grid voltage is high in order to reduce electrical losses and the size and weight of transmission cables.

The voltage “step-up” between the wind turbine and the grid is accomplished by transformers [5]. The transformer can be either inside the nacelle or at the base of the tower. The conventional transformer for wind turbines is made of magnetic materials and has copper windings. It is heavy and bulky: it can weigh tens of tons and contribute up to 30 percent of the overall system weight. However, the transformer does not need to be in the nacelle but can be at the base of the turbine or nearby, and therefore weight is not as important a consideration as it is for gearboxes and generators.

The successor of the conventional transformer, still in the research stage, may be the solid-state transformer, which uses power electronics to manipulate voltages and is much smaller and lighter. This emergent technology leverages the broad advances in semiconductors of recent decades. The major benefit of the solid-state transformer is that it allows greater flexibility in connecting the wind turbine to the grid. Reducing its cost and improving its reliability are the current challenges, here and throughout the wind turbine’s innovation frontier.

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Article 7: Wind Farms

It is typical for tens to hundreds of turbines to be built together in what is called a wind farm. In a wind farm the turbines' supporting infrastructure and operational resources can be shared. The proximity of turbines to one another adds complexity in that they can interact with each other aerodynamically through their wakes, generally reducing the total output of the farm relative to the sum of the outputs if each turbine had operated in the absence of the other ones. This article describes the factors that are considered in siting, construction, and maintenance of wind farms both onshore and offshore. We also discuss the impacts of wind farms on their local environments.

7.1 Siting

Turbines are sited in clusters, typically from 10 to 100, in wind farms. These are projects, with common ownership, coordinated maintenance, and one or more customers. A relatively new, large onshore wind farm in U.S. might host 60 three-megawatt turbines, or a total of 180 megawatts of rated capacity.

A wind developer choosing a site for a wind farm seeks a site with high average wind speed and little variation in the speed. A steady wind direction is also advantageous, because it allows a placement of individual turbines within a wind farm that minimizes the sheltering that occurs when a downwind turbine is sitting in the wake of an upwind turbine. Environmental and societal impacts weigh heavily as well, including wildlife impacts, noise, and aesthetic concerns. Offshore siting decisions take shipping lanes, fishing grounds, and other uses of the sea into account.

The wind at any potential site is best evaluated at the height where the hub of the wind turbine will be located, and (for onshore sites) with the presence of surface obstacles like buildings and trees taken into account. Typically, a temporary meteorological mast is deployed to obtain these measurements, which are compared with data from nearby sites and longer-term records [1]. Later, a permanent mast will be installed at the chosen site to monitor ongoing performance.

Siting Onshore

When there is not already adequate supporting infrastructure, additional infrastructure must be built. For onshore sites this may entail the construction of roads, and for offshore sites this will require ports and ships. The adequacy and accessibility of available transmission lines is especially critical and can affect the timing and size of proposed wind farms.

Siting decisions for onshore turbines often involve negotiations with multiple land owners, who must grant a lease or easement and typically receive royalties for use of the land. If rights to a sufficiently large contiguous plot of land cannot be acquired, a planned farm may become two farms with land between them that is not part of either farm.

Siting Offshore

Offshore wind projects are an increasing fraction of all wind projects. Winds are typically both stronger and more consistent offshore, resulting in a higher capacity factor for the wind farm. Wind turbines can be made bigger offshore than onshore, because onshore turbine size is limited by difficulties with road transport. Wind farms can often be located closer to coastal cities than their onshore counterparts. In some locations, offshore wind patterns are better matched to electricity demand over a typical day; offshore along the U.S. East Coast, for example, wind power generally peaks in the afternoon or evening, near the time when power demand also peaks [2].

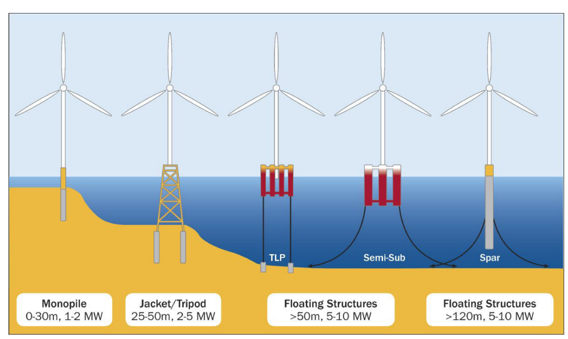

Figure 7.1: Typical foundation types for offshore wind turbines, from shallow waters (left) to deeper waters (right). Source: Bailey, Brookes, Thompson, https://aquaticbiosystems.biomedcentral.com/articles/10.1186/2046-9063-10-8.

Figure 7.2: Photo of the Horns Rev Wind Farm offshore in Denmark, with the complexity of wind turbine wakes made visible by fog. Red circles have been added to identify a turbine in the second through fifth rows behind the leading row of turbines. Source: Vattenfall, https://www.climate.gov/news-features/featured-images/wind-turbines-churn-air-over-north-sea. Red circles added by authors.

Over time, as with offshore drilling for oil and gas, gradual movement into deeper waters can be anticipated, because nearer-to-shore sites will have been developed and because there will be sites where winds are superior. Figure 7.1 shows a possible march of platform types, outward from the coast.

7.2 Interactions Between Turbines

Turbine spacing is an important factor when laying out a wind farm; it will determine the total number of turbines that a site can accommodate. If the turbines are unnecessarily far apart, the land is used inefficiently. If the turbines are too close together, the turbines experience large fluctuating loads from the wakes of other turbines, which increases the farm's maintenance costs and reduces its power output. Wind farms are designed to mitigate these wake-turbine interactions, as well as wake-wake interactions.

A well-known photo of a Danish multi-row offshore wind farm (Horns Rev 1) on a day when atmospheric conditions permitted exceptionally visible wakes is reproduced in Figure 7.2. Relative to the first row, the wind impinging on the second and subsequent rows is much more complicated.

If a dominant wind direction exists on the site, a farm's turbines may be positioned in fewer rows facing the wind, with larger numbers of turbines in each row. The turbines may also be spaced more closely along the rows than between rows. Successive rows of turbines can also be either aligned or staggered. In an aligned layout, where all turbines sit directly in the wakes of other turbines, the turbines after the first row experience a lower incoming velocity and thus generate less power [3]. In a staggered layout, output power is larger because the turbines experience only a part of the wakes of other turbines, but the wind loading across the turbine blades is more unequal, which increases the stresses on the blades and other turbine components and increases maintenance. Figure 7.3 shows an idealized staggered layout for a prevailing wind.

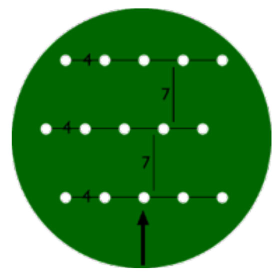

Figure 7.3: A representative staggered configuration of turbines (shown as white dots) relative to the prevailing wind direction (black arrow). The numbers are distances, measured in diameters of the circle traced by the tip of a blade – roughly twice the radius of the blade. So, the turbines here are spaced 4 diameters apart in the direction transverse to the prevailing wind and 7 diameters apart in the direction of the prevailing wind. Source: Guided Tour on Wind Energy, 2011, DWTMA; Delft University of Technology, http://mstudioblackboard.tudelft.nl/duwind/Wind%20energy%20online%20reader/Static_pages/park_effect.htm.

7.3 Construction

Roads may be the first priority in the construction of an onshore wind farm, in order to enable transport of materials to the site. Figure 7.4 displays a pair of trucks transporting a blade through an intersection, which is clearly a tight fit; sometimes roads are created solely for this purpose.

Construction of turbine foundations, drainage, and the electrical network proceeds in parallel. The electrical network includes transformers, power cables, switchgear, and data lines for the control center. Transformers at each turbine raise its output voltage, then the outputs from the farm's turbines are combined, and then the voltage is raised a second time so that the farm's power matches the voltage of the local power network [4]. The cables connecting the turbines to a substation or grid interconnection can run either underground or above ground on posts. While overhead cables are cheaper, they complicate the access of trucks and cranes to the turbines for construction and maintenance and make the system more prone to storm damage. Additionally, above-ground cables and supporting posts are not visually appealing, which can affect project approval.

The foundation and mooring for an offshore turbine are significantly more expensive than for an onshore turbine. We do not discuss offshore construction issues here.

7.4 Operation and Maintenance

The operation of a wind farm is run from a control center that processes information gleaned from meteorological equipment and a network of sensors at each turbine. Site operators monitor the operation of the turbines and can override the automated control system. Increasingly, a third party (neither the equipment manufacturer nor the wind power developer) provides the control center.

Wind power generation is a complex process with many pieces of equipment, including both moving and stationary mechanical components and a broad array of electrical systems. One reason that wind turbines are clustered within wind farms is to make maintenance less costly. Maintenance crews can move quickly and easily from one turbine to another, whether performing planned maintenance that keeps the turbines operating at high efficiency and availability, or corrective maintenance to repair faults when they arise. (Availability is the percentage of time that a turbine is available to produce power when asked.) Maintenance is typically covered by a service contract with the original turbine manufacturer or a separate company.

The frequency of maintenance will depend upon the type of equipment and its likelihood of failure, the operating history of the equipment, and the age of the plant. Sites experiencing harsh winters or high winds may need more maintenance than sites with less extreme weather. However, since all wind turbines are subject to frequently varying wind, every turbine demands regular maintenance and check-ups a few times per year. Regular maintenance ensures that the gearbox, generator, various bearings, and the braking system are in good condition and are properly lubricated. In addition to reducing the chance of failure, this increases the lifetime of the turbine, just as oil changes help to extend the life of a vehicle. Blades are cleaned to prevent their surfaces from becoming roughened due to buildup of debris and insects; even a small unevenness in the blade's shape has detrimental effects on power output.

Maintenance costs are falling as wind turbines incorporate new techniques. For example, drone-mounted cameras and sensors are now used for evaluating damage to blades, a task that would otherwise be dangerous, costly, and time-consuming – given the awkward location of the blades. Drones delivering an antifreeze fluid supply also simplify the de-icing of blades in winter. "Smart" blades with integrated sensors are enabling advanced data analysis techniques to analyze turbine power output, supplementing visual inspection.

Automation allows maintenance crews to work mostly during the day and to be backed up by remote monitoring crews who evaluate the site continuously for faults and decide when to call out the maintenance crews for urgent matters. In some cases, it may not be advisable to conduct maintenance immediately following the failure of a part. For example, if a turbine fails during the night, it may be safer and more cost-effective to wait until the daytime maintenance crew arrives, rather than employing a 24-hour maintenance crew.

The turbines at a wind farm are not necessarily all roughly alike. There are advantages and disadvantages. Operating only one type of turbine at a farm reduces operator training time and the number of spare parts that must be stocked. Operation and routine maintenance are simplified. Nonetheless, some wind farms deliberately diversify the kinds of turbines installed in order to ensure continued operation when a specific type of turbine needs attention [5] and to guard against common-mode failure. As data acquisition and monitoring become more compatible across the wind industry, the control of a wind farm with two or more turbine types is facilitated.

Figure 7.4: Source: Wind turbine blade, 274 feet (more than 80 meters) long, navigating a turn on its journey from Denmark to an experimental offshore turbine in Scotland. Source: SSP Technology, http://www.ssptech.com/solutions/blades/.

Maintenance Offshore

Maintenance is more difficult for offshore than onshore turbines. Poor weather can necessitate waiting several days or more before a maintenance crew can get onsite for repairs following a breakdown. It therefore pays to make offshore turbines significantly larger. The capacity of a typical new onshore turbine is three megawatts, compared to six megawatts for an offshore turbine, and designs of 12 megawatts and above may be the offshore norm in the near future.

A major consideration for offshore turbines compared with onshore turbines is corrosion. The materials used for the components of an offshore turbine must be corrosion-resistant or they must have robust coatings, increasing costs. Some offshore turbines have a sealed and dehumidified nacelle that prevents moist, salty air from entering.

7.5 Environmental Impacts

Wind farms affect the local environment in many ways. Visual impacts and noise are particularly important, but there are also microclimate impacts on farming, and direct detrimental impacts on other species, notably birds and bats. Indirect impacts are associated with the energy use embodied in the wind farm's components and incurred during its construction.

Visual Impact

The visual impacts of a turbine are both near and distant. Nearby impacts for land-based wind turbines include shadows and flicker. With multiple turbines rotating in a wind farm, the flicker can be more prominent as the blades intercept sunlight at different times. As for the more distant impacts of wind farms, these are sometimes framed as intrusions on landscapes or seascapes and have driven siting decisions in many instances. Onshore, consideration of only the most desirable winds can point to a site on a mountain ridge, but this may be where hikers have their most treasured views. Offshore, at least in the U.S., the distance of a wind farm from land can be pushed upward by political pressure from coastal communities concerned about property values and seascapes.

Wind turbine projects offshore may soon involve 12-megawatt turbines. The blades of one such turbine are 110 meters long and their tower is 150 meters tall, so the tip of a blade straight up extends to 260 meters. If sited 30 kilometers (20 miles) from the shore, the tops of the towers in the daytime, viewed from the shore on a clear day, would be short faint straight lines sticking upward out of the ocean. The lights at the tops of the towers that warn aircraft would be visible from the shore on a clear night. A sense of the size of such a turbine is conveyed by Figure 7.5. The heights listed for the turbines are the distance from the top of a blade pointing straight up to the ground or ocean surface underneath.

Noise

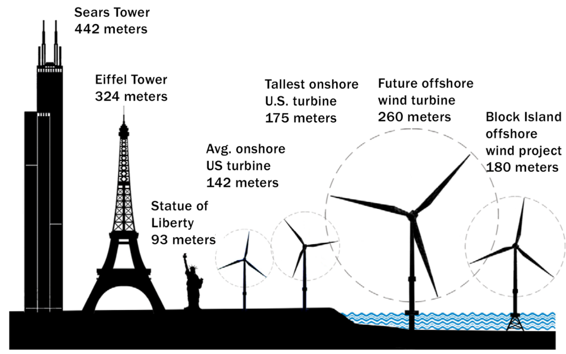

Figure 7.5: Offshore wind turbines are already as large as the largest wind turbines and are slated to become much larger. Wind turbine sizes are compared to the Sears Tower in Chicago, Statue of Liberty in New York City, and Eiffel Tower in Paris. Dashed circle indicates the path of the blade tip. One meter is 3.28 feet. Source: Bumper DeJesus, Andlinger Center for Energy and the Environment.

As the blades of a turbine rotate, they generate pulsating sound at both audible and sub-audible frequencies. The audible component can adversely affect health by producing stress, headaches, and troubled sleep [6]. Since wind farms are generally located in areas that do not have large structures around them (as that would impede the wind), the noise from a turbine propagates easily. Moreover, the noise from a wind turbine is greater when the blades rotate faster. As a result, turbines are designed with a ceiling on their rotation rate.
In Figure 7.6, an auditory impact map from a study of a wind farm in Maine is shown. Here the color scale

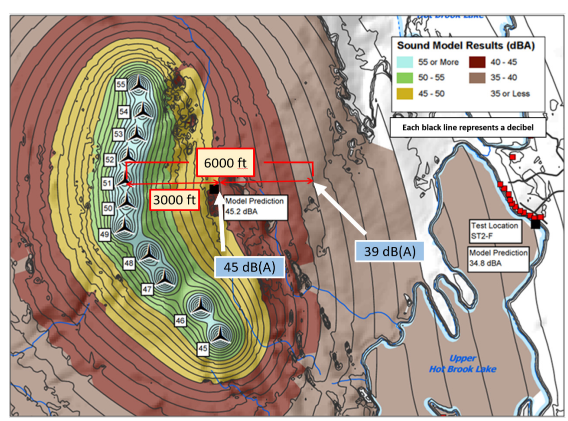

Figure 7.6: Simulations of the noise impact for a hypothetical wind farm along a ridge in Maine. Source: Prepared for VPIRG by Bodwell EnviroAcoustics, https://www.vpirg.org/issues/clean-energy/wind-power/faq/.

is shown in decibels, a measure of sound intensity. The noise level decreases when moving away from the turbines, which form a row down the left side of the map. The decibel contours for 45 and 39 decibels are highlighted and are roughly 3,000 and 6,000 feet (1,000 and 2,000 meters) from the turbines, respectively. This study influenced a decision by the State of Vermont to require that the noise at night from any wind farm built in the state cannot exceed 39 decibels immediately outside any residence.

Microclimate

Large onshore wind farms increase the turbulence of the air and decrease the local wind speed as energy is extracted by the turbines, resulting in a unique “wind farm microclimate” [7]. In many cases it is unclear how the farm will affect features of the local environment such as temperatures, heat fluxes, moisture in soil, and rainfall. Simulations suggest that wind turbines increase the transport to the Earth’s surface of the drier air high in the atmosphere, which increases evaporation and transpiration [8] and modifies the energy exchanges between the surface and the atmosphere [9]. A study in 2012 conjectured that wind turbines were partially responsible for a 0.7 degree Celsius (1.3 degree Fahrenheit) nighttime warming over 10 years in a large area of west-central Texas [10]; the wind turbines may be disrupting nighttime stratification of cold air close to the ground by mixing it with warmer air above.

Impacts on Wildlife

The effects of onshore wind farms on plants and animals in surrounding areas can strongly affect their siting. The rotation of the blades of a wind turbine can kill birds and bats. Wind turbines can also indirectly influence the migration routes of birds, their patterns in flight, and their choices of habitats for foraging, breeding, and nesting [11].

To mitigate these impacts, wind farms can be located away from migration corridors and nesting and roosting sites. In some instances (more for bats than for birds), wind farm operation is curtailed at certain times of the year and in certain low-wind conditions [12]. Turbines and blades have been modified to make them easier for birds and bats to detect; as the blades get larger, they will become easier to detect, and the incidence of bird and bat fatalities should fall. As for other terrestrial animals, the main negative impacts are during construction.

On the other side of the ledger, there is evidence that wind turbines may actually improve plant growth, since warmer air pushed downwards during the evening hours may prevent dew from forming on the leaves and reduce mold. Livestock often graze right up to the base of a turbine and can use its shadow for shade.

For offshore wind farms, the permitting process may require explicit consideration not only of plant construction but also of plant decommissioning several decades after the installation, with requirements in both cases for specific attention to measures that will minimize disturbance to marine life [13].

Embodied Energy, Land, Material, and Water Use

Water and energy are required to construct and operate a wind farm. Water inputs for wind power are minimal during construction and operation [14] – somewhat lower than for solar power, which requires water for the fabrication of solar cells, and much lower than for power from coal, natural gas, and nuclear power, where the power plants use water both during construction and for cooling when they are operating. The largest energy inputs to a wind turbine occur where the concrete, steel, and other materials are made. Estimates of the energy payback (the time required for the wind turbine to produce as much energy as was required for its fabrication and installation) depend on the specific site but are generally around six months [15]; turbines running at high capacity and in high winds generally have shorter payback times. While running, wind turbines have no air pollution or carbon emissions other than minor on-site emissions associated with auxiliary operations.

By weight, steel, copper, and concrete are the primary materials. Permanent magnets, used in an increasing fraction of new turbines, also use rare-earth minerals such as neodymium, dysprosium, and terbium. While there are supply concerns, the global resources themselves appear to be adequate, relative to projections of future needs for wind power [16].

Because wind turbines must be far apart so that one turbine does not adversely affect the performance of another, a wind farm occupies a lot of land. However, uniquely, a wind farm is compatible with many other uses of the land, including agriculture and animal grazing. Wind farms modify the land significantly less than coal mining, oil and gas extraction, solar farms, or biomass plantations [17].

End-of-Life Considerations

As the wind industry matures, valuable experience is being gained about the trade-off between keeping a component running and replacing it – typically with a component that is more efficient and requires less maintenance. Large-scale replacement, called “repowering,” may involve the swapping of major turbine components (the blades, the generator) [18]. An after-market for the replaced equipment is developing, enabling some of the costs of repowering to be offset. Some steel and copper will be reused and some recycled [19].

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Article 8: Managing a Grid when Variable Wind is Prominent

As wind becomes a more prominent contributor to electricity supply, its variability complicates grid operation on ranges of timescales, from seconds to days to months. The duration of the mismatch between supply and demand (the length of the lull) determines the optimal response, which is some mix of flexible power from other sources, access to more distant winds, energy storage, and demand-side management. Prominent wind power also creates requirements for wind turbines to be able to help reduce the consequences of unforeseen grid disruptions; wind turbines are becoming increasingly helpful.

8.1 The Grid Before Wind

An electricity grid consists of many individual generators of electricity, connected via power lines to consumers. Most of the power is generated by large units (coal and gas plants, hydroelectric power plants, and nuclear power plants), most of them having typical installed capacities in the hundreds of megawatts or larger. These unit capacities are hundreds of times larger than our reference three-megawatt wind turbine, but comparable in capacity to the larger wind farms.

All present-day electricity systems share a common requirement: at every instant, electricity demand from consumers must be met with an equal supply from generators. Very little electricity is stored from one instant to the next. Electricity demand is inherently variable. The time of day, the weather, and the season all impact the quantity of electricity that consumers demand. A century of experience has shown that grids can be operated successfully, even though there is significant demand variability at every time scale.

The introduction of wind power (and solar power) into the grid complicates the supply-demand balancing. Now, not only does demand vary, but available supply does too. The same strategies that enable a reliable grid in the face of variable demand become even more important.

The electricity market of the State of Texas presents a helpful example, to which we refer three times in this article. Texas is the only one of the 48 contiguous U.S. states which has its own electricity grid, largely isolated from two much larger grids that connect the other states.[1] As a measure of its isolation, the external interconnection capacity of the Texas grid is equal to just 1.4 percent of the total capacity of its energy generators [1, 2]. Figure 8.1 shows typical patterns of total electricity demand over a late-March week in 2017 and over that entire year. Hourly consumption during that week (and probably all weeks) is greater during the day than at night. The variation in demand over a year shows the expected summer peak in warm climates due to high demand from air conditioners. Much of this variability

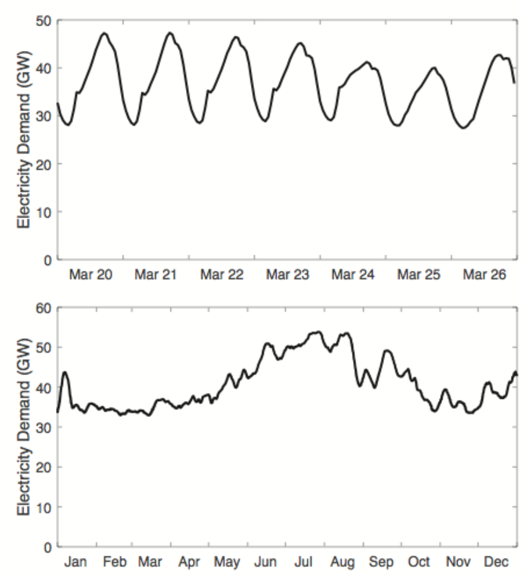

Figure 8.1: Electricity demand in Texas on two different time scales. 1 GW is 1,000 megawatts. *Top:* Hourly demand during one week, from March 20-26, 2017. *Bottom:* Demand for all of 2017, shown as a 168-hour (one-week) running average of hourly data. Data source: [3].

[1]For simplification, we refer frequently in this article to Texas data, when the data are actually from the service area of the Electric Reliability Council of Texas (ERCOT), which includes nearly all of Texas. ERCOT manages about 90 percent of the Texas electricity market.

can be accurately predicted based on a combination of historical data and weather forecasting. The annual data also show two weather-driven features: 1) a short period of high demand associated with a cold snap in January 2017, and 2) an abrupt drop in demand in August 2017 associated with Hurricane Harvey, which knocked out much of the electricity grid along the Gulf Coast.

8.2 Integrating Variable Wind

To illustrate the potential for mismatches between variable supply and variable demand, we return to Texas. The Texas grid has the highest installed wind capacity of any state: at the end of 2017, 21,000 megawatts were installed [3]. Wind turbines produced 17 percent of the state's electricity, and natural gas power plants produced 39 percent [4].

Figure 8.2, top panel, repeats the curve in the top panel of Figure 8.1 that shows Texas electricity demand during a week in March 2017. The same panel shows, as well, wind power production during that week. Wind power supplied about one quarter (28 percent) of total electricity generation that week [4]; production was well below total demand all week, and wind output did not align with detailed consumption very well.

The bottom panel of Figure 8.2 shows a counterfactual case where Texas experiences the same pattern of wind power production across the week, but the amount of power is multiplied uniformly by a number (a little less than 4), chosen so that the week's total wind power equals the week's total demand. The week contains four periods of extra wind that alternate with four periods where wind power is insufficient.

Imagine that all of the excess wind power in the idealized energy system were stored and then used during the times of under-supply. The wind power input would meet demand exactly throughout the week.
To be sure, this result requires the storage system to operate with no energy losses; in fact, there are always energy losses whenever a storage system acquires or discharges energy. For an energy system that even slightly resembles the one shown in Figure 8.2 in its prospective periods of excess and shortfall in energy supply, energy storage would be only one of many strategies to rebalance the system.

Two countries where wind power already accounts for a large fraction of annual electricity production are Ireland (21 percent in 2016 [5]) and Denmark (44 percent in 2017 [6]). Like Texas, the Ireland grid is relatively isolated, with only a 9 percent interconnection capacity [7]. Also like Texas, Ireland achieves wind integration primarily with natural gas, which accounts for about 44 percent of Ireland's electricity [8]. Denmark, by contrast, has relatively little gas generation to balance its high penetration of wind; its second largest electricity source is coal, which provides 25 percent of its electricity [9].

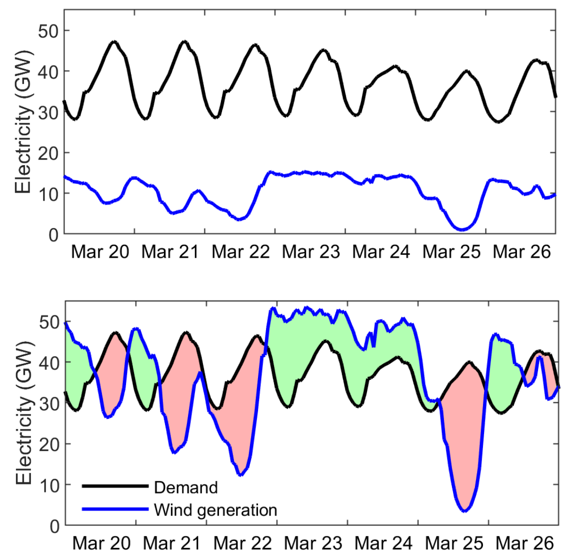

Figure 8.2: ***Top:*** **Actual electricity demand and wind generation in Texas, March 20-26, 2017 [3].** ***Bottom:*** **Wind capacity, rescaled to create the counterfactual situation where the total wind generation that week equals the total electricity demand, and no other changes are made. Green and red shaded areas represent excess wind and a deficit of wind, respectively.**

Denmark's principal strategy for handling its lows and highs in wind-powered electricity is to use its strong interconnections with the electricity grids of surrounding countries, including the much larger German grid to the south and the flexible hydropower assets of Norway to the north. Its total interconnection capacity is 44 percent of the country's total installed electric capacity [7]. Wind generation in Denmark can exceed 100 percent of its total in-country demand during high-wind periods without creating problems for its grid.

Grid Flexibility

The principal way a current grid deals with threatened mismatches between supply and demand, when the mismatch is for short times (from seconds to hours), is to call on sources of electricity that can ramp their power production up and down quickly. Gas turbines (which are much like airplane engines) are suited for this assignment, "load-following," as are hydropower facilities in many cases. Batteries are also helping with load balancing, more and more as their costs fall.

A traditional fossil-fuel power plant experiences substantial extra costs when its output power varies often: its operating lifetime and its efficiency decrease, and it requires increased maintenance. Demands for operational flexibility are harder on older ("legacy") coal and natural gas plants than the new natural gas plants being added to grids, whose designs, to a greater degree, anticipate frequent calls for changes in output [10, 11, 12]. Looking ahead to grids with incentives to lower their carbon dioxide emissions, a successor

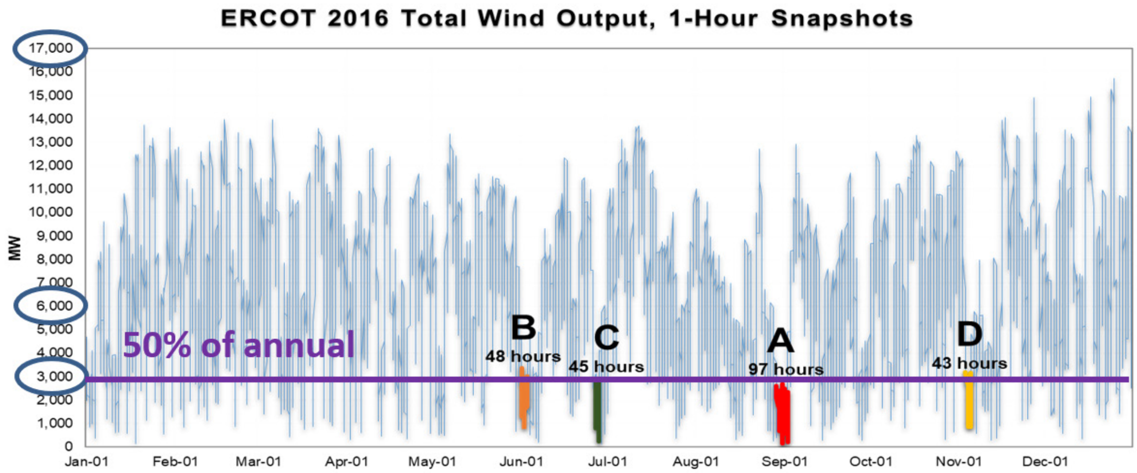

Figure 8.3: Hourly total electricity production from the wind farms in the ERCOT service area in 2016. Three values are identified on the vertical axis: 17,000 megawatts is the total capacity of the wind farms; 6,000 megawatts is the annual average wind power production; and 3,000 megawatts is half of the annual average – the threshold we have chosen for the illustrative analysis here. The four longest lulls are labeled A, B, C, and D. Source: [14].

generation of natural gas plants may arrive that capture the carbon dioxide produced when burning the fuel. The carbon dioxide, which otherwise would be emitted to the atmosphere, could be pumped into deep underground geological storage reservoirs.

When a mismatch is to be avoided and available wind power is in excess, the sale of wind power can be curtailed: the wind turbine operator would be told that not all output can be placed on the grid. The unsold power is said to be "spilled." In addition, some other electricity generators can be told to produce power only at certain hours; for example, a coal plant or a hydroelectric dam would be scheduled to run during the day but not at night.

Another strategy that can be pursued by the electricity generation system is to invest in transmission lines that access distant winds which are strong when local winds are weak, and vice versa, thereby smoothing out wind's contribution to the grid while at the same time creating a larger market. More generally, expanded transmission and distribution capability enables greater diversification across power generators; for example, it may foster the export of excess solar power from one region at midday to a second region where winds have subsided at the same time. The Competitive Renewable Energy Zone in Texas, which connects the state's major cities to sites in western Texas favorable to wind and solar generation, is an example. The costs of financing the transmission lines are borne by the state's electricity consumers; the benefit is greater diversification in electricity generation and a larger presence for wind and solar power [13].

Still another enabler of high wind penetration is more flexible electricity demand ("demand-side management"). The timing of delivery of electric power to a water heater or electric car battery, for example, can be put under the control of the grid operator. Customer buy-in is fostered when there are time-variable electricity prices and smart appliances that are programmed to benefit from these prices. It becomes profitable for all parties when a washing machine is operated on a windy day rather than a calm day, for example.

8.3 Lull Analysis and Long Lulls

An interesting way to appreciate the variability of the wind is to use "lull analysis" [14]. A lull is a period of definite duration when the wind speed is below some threshold. A lull might last from a few seconds to several days. In Figure 8.3 we return to Texas once more to demonstrate a lull analysis. Hourly wind production is shown for an entire year, 2016. At the end of 2016, the total installed wind capacity of the Texas wind farms was about 17,000 megawatts and during that year the rate of wind-power production averaged 6,000 megawatts. For this analysis, we arbitrarily select the threshold to be half the annual average value, or 3,000 megawatts, shown as a horizontal line in Figure 8.3. A lull begins when wind power output first falls below 3,000 megawatts and ends when it first ascends above that value.

Starting with the first hour of the year, we can note every hour when total wind power falls below the threshold and also note when it first crosses back to a value that exceeds the threshold. It turns out that there were 219 of these lulls in 2016. Their average duration was 9 hours, and 75 percent of them lasted less than 12 hours. Only five percent of lulls (12 lulls) lasted more than a day. (Applying the same methodology but defining a lull using the lower threshold of 1,500 megawatts, which is 25 percent of annual average power, the longest lull lasted only 20 hours.) The four longest lulls are labeled A, B, C, and D, in Figure 8.3. Event A lasted roughly four days, and events B, C, and D lasted roughly two days – a total of ten days for the four events.

Long lulls will elicit very different responses than short lulls. Batteries (as well as other storage strategies whose cost is roughly proportional to the energy they store) may compensate well for short lulls, but not for long lulls. Innovative responses to long lulls will be necessary – notably, generation technologies that are profitable even when alternating between running and not running for months at a time. One can imagine differential consumer behavior during long lulls, the counterpart to behaviors during “snow days,” when schools are closed, but more like “harvest months,” when schools are closed because children participate in bringing in the crops.

The variability of wind is a challenge that cannot be wished away. Even if wind power were free while still as variable, its ability to become a major contributor to power generation for any large region would require many forms of accommodation that are just beginning to be developed.

8.4 Grid Stability and Grid Services

Events that can disrupt the operation of the grid can occur over timescales from seconds (heavy machinery turning on or off, failure of a generator or transmission line) through hours, days, and months (power plant shutdown, routine maintenance). To minimize these vulnerabilities, the operator of a power grid takes account of specific features of each generator, such as its size, its start-up time, the maximum rates at which it can increase and decrease its output (its “ramping” rates), and its costs for electricity production. The grid operator also considers transmission constraints.

Disruptions to the grid appear as frequency or voltage reductions. Frequency reductions are caused by a generator disconnecting from the grid or a new load coming online. Voltage reductions result from electrical circuit faults. Such drops create problems for those electricity consumers requiring high-quality power.

In a minor frequency disruption, the grid frequency remains within its narrow “dead band” of permitted frequencies – departures from the reference frequency limited to roughly 0.02 cycles per second (1 part in 3,000 for a 60 cycle-per-second grid). A larger disruption results in the grid frequency falling below the bottom of the dead band.

The conventional steam and gas power plants on the grid can counter a drop in frequency or voltage in two ways. First, those that are running below maximum power output can be programed to respond automatically with additional power generation over the first few seconds, stabilizing the grid within a few minutes [15]. These power plants have deliberately held some generation capability in reserve to respond to such contingencies. Second, because their generators are all synchronized with the grid, these plants can also add power to the grid by showing down their rotating machinery. This supplementary response is even faster (it occurs over tenths of a second), but it generally has less overall effect [16].

The first wind turbines that produced grid power played little role in stabilizing the grid during a sudden and significant disruptive event. Typically, the wind turbines on a grid were immediately disconnected from it, as were other smaller, geographically dispersed {“distributed”) energy resources, like solar arrays. But, as distributed generators on the grid became more numerous, a threat to the stability of the grid emerged where all of these generators could simultaneously disconnect during a grid disruption and turn a minor event into an event with cascading impacts, where each turbine shut-down makes the grid anomaly worse. Both grid managers and the wind industry realized that wind turbines needed to be modified so that they could contribute toward minimizing the consequences of any grid disruption. Such modifications become especially important when distributed energy sources are providing a large fraction of total power, such as when winds are strong and the load is light.

Grid operators, starting in Europe, have been issuing new rules that apply to all power sources, including wind turbines. The rules essentially require every wind farm to stay online during grid disruptions and to regulate its output power to keep its characteristics within narrowly specified ranges. These requirements govern the voltage, frequency (cycles per second), and shape of the oscillations of the alternating current (AC) electricity. Wind turbine developers are responding to these new rules by equipping the turbine with new control capabilities and operating procedures [17].

A modern wind turbine counters a wayward fall in frequency with strategies that are similar to those provided by conventional power plants. To be able to provide extra power quickly on demand (the grid may request as much as an additional ten percent of its rated power), it must not already be producing power at its maximum value for that wind speed. Instead, it must deliberately produce less power than it could, thereby creating the “headroom” to respond for a call from the grid for extra power. Such headroom can be achieved by setting the pitch of the blades in normal operation slightly away from optimal or orienting the turbine slightly away from straight into the wind. Since there is a loss of revenue when operating with headroom, the wind farm must be either incentivized or required to operate in this manner [17, 18]. The most recently installed wind turbines can also contribute extra electricity to the grid to compensate for a falling frequency by using power electronics to reduce the rotational speed of the blades and other rotating components [19]. Earlier wind turbines did not have this capability.

A wind turbine with modern power electronics can also help control a grid's voltage deviations. It can support voltage stability even when the turbine is not producing power at all.

Farm-level Grid Services

Wind power can provide grid services at the level of the wind farm, not only at the level of the individual turbine. With the help of power electronics and advanced turbines, the operator of a wind farm can coordinate the outputs of each of the farm's turbines to keep the farm's total output within narrow limits and to control the rate at which total output ramps upward or downward. Consider the two-hour field test reported in Figure 8.4. Prior to the onset of the test, a 30-megawatt wind farm is operating at far below its rated power under nearly constant high winds (just above 15 meters per second) – at only 10 megawatts; this could be the result of some strict curtailment. During the first 90 minutes, the farm output's climbs upward in the same high winds back to 30 megawatts in four five-megawatt steps, each accomplished in approximately three minutes, with output tightly controlled at each step [20].

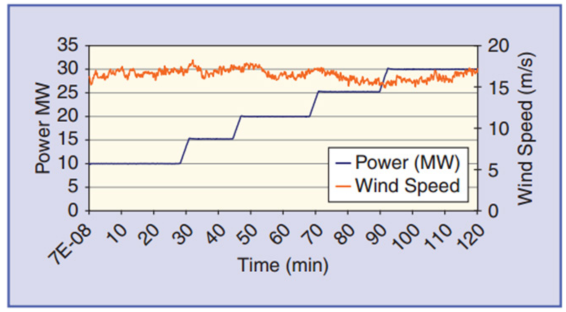

Figure 8.4: Controlled upward ramping of a wind turbine farm's output power. MW: megawatts; m/s: meters per second. Source: [20].

In short, "grid friendly" wind power is becoming the new norm.

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