9 Siting

The crucial factor in siting a wind turbine or wind farm (also called wind park or wind plant) is the annual energy production and how the value of the energy produced compares to other sources of energy. Data from meteorological stations worldwide are are of little use when predicting wind power potential and expected energy production from wind turbines.

9.1 SMALL WIND TURBINES

For small wind turbines, a measuring program may cost more than the turbine; therefore, other types of information are needed. Many countries are developing wind maps to aid development of wind farms. These maps can be used as guides to determine regions that have enough wind for small wind turbines. Also, wind maps for countries and large regions obtained from numerical models have sufficient resolution for determining general areas for siting small wind turbines. In the United States, WINDEXchange provides residential scale wind speed maps at 30 m for every state [1].

An annual average wind speed of around 4 m/s and greater is considered suitable for small wind projects. Tower heights for small wind turbines range from 10 to 35 m. Because small wind turbines are located close to loads, local topography will influence the estimations of wind speeds and siting decisions. If a location is on exposed terrain, hills, or ridges, wind speeds will be higher than speeds in a valley. In complex terrain, some sites will be adequate for small wind turbines and some will be too sheltered.

One of the important factors in the settlement of the Great Plains of the United States was that farm windmills could provide water for people and livestock. Therefore, if farm windmills are used or were used in the past in a region, the wind is sufficient for the use of small wind turbines in the region. Another possibility is to install met towers to compile reference data for a region. Generally, this is done by regional or state organizations or governments, not by individuals interested in siting small wind turbines.

Small wind turbines can be cost effective as stand-alone systems using the general rule that the average wind speed for the lowest wind month should be 3–4 m/s. General maps of wind power or wind energy potential for small wind turbines have been developed for large regions (Figure 9.1) [2]. These gross wind maps will be replaced by national wind maps developed for determining wind energy potential for wind farms. Finally, if wind farms already exist in an area, the wind is sufficient for small wind turbines.

It is obvious that a small wind turbine should be located above (10 m if possible) obstructions and away from buildings and trees [3]. Towers for small wind turbines should be a minimum of 10 m and preferably 20 m high; higher towers generally capture more energy (Figure 9.2). Again, the trade-off is the extra energy versus the cost of a taller tower. Towers of 35-m height are sometimes used.

As a general rule for avoiding most of the adverse effects of building wakes, a turbine should be located: (1) upwind of the prominent wind direction, or maybe the prominent wind direction of low wind months at a distance more than two times the height of the building, (2) downwind a minimum distance of ten times the building height, or (3) at least twice the building height above ground if the turbine is immediately downwind of the building. The above rule is not foolproof because the size of the wake also depends on the building's shape and orientation to the wind (Figure 9.3).

Downwind from a building, power losses become small at a distance equal to 15 times the building height. However, a small wind turbine cannot be located too far away from the load because the cost of wiring over a long distance is prohibitive. Also, more losses in wires will occur

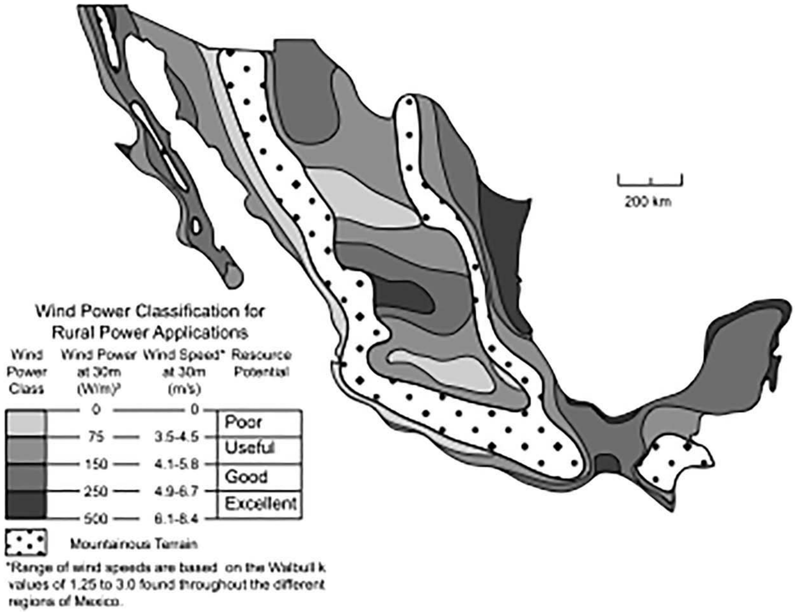

FIGURE 9.1 Wind power map for rural applications in Mexico. Notice the difference in the definition of wind power class and height, which is at 30 m.

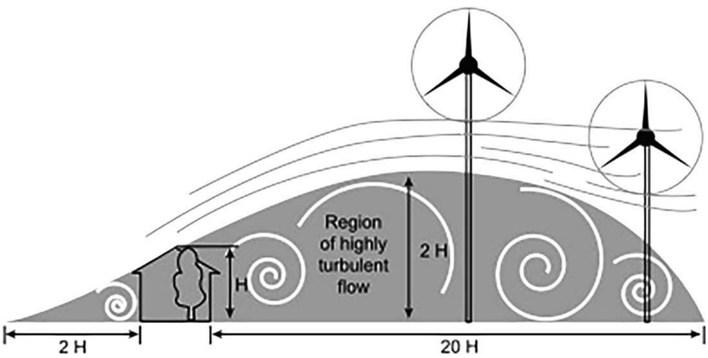

FIGURE 9.2 Height of a small wind turbine close to obstacles of height H.

if DC rather than AC transmits power from the wind turbine to the load. In general, small wind turbines should not be mounted on occupied buildings because of possible noise, vibration, and even turbulence. Tower heights for very small wind turbines vary from stub poles on sailboats to short (3–5 m) towers, and some are even mounted on buildings. Paul Gipe wrote numerous articles on all aspects of wind energy [4], and two of his books are about small wind systems [5,6].

Is there such a concept as wind rights if a neighbor erects a tall structure that obstructs the flow of wind to your turbine? From a visual standpoint, a wind turbine in every backyard in a residential neighborhood is much different from a photovoltaic (PV) panel on the roof of every home.

The Distributed Wind Energy Association [7] has online information about small wind turbines including information on siting. A *Small Wind Guidebook* has a section on siting and can be downloaded from the U.S. DOE, EERE (https://windexchange.energy.gov/small-wind-guidebook) An older guide for small wind turbines available from the National Renewable Energy Laboratory (NREL) [8] also contains similar information about siting.

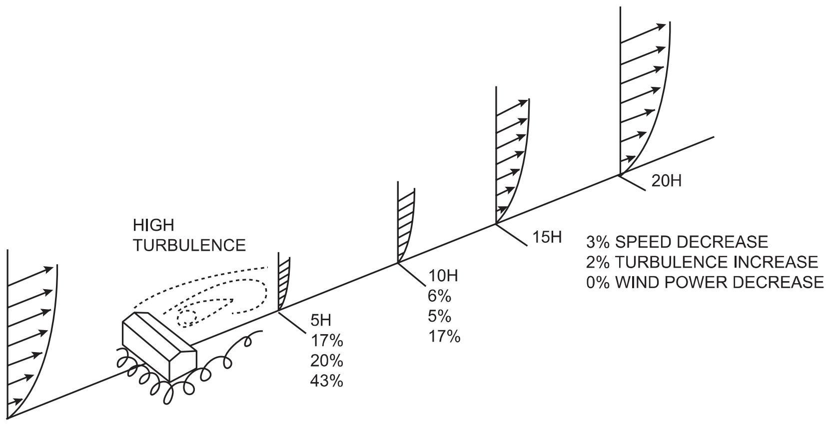

FIGURE 9.3 Estimate of speed, power decrease, and turbulence increase for flow over building. Estimates shown are for building height H. (M.M. Schwartz and D.L. Eliott. 1995. In *Proceedings of Windpower Conference*. With permission.)

RenewableUK, formerly the British Wind Energy Association, maintains a section on small and medium wind turbines [9] that includes information on the national wind speed database, small wind turbine technologies, planning, and case studies. An interactive map for wind speeds at 10, 25, and 45 m is available online [10], and the RenSmart Site Planner estimates energy production, yearly value, and pay-back time for wind and solar systems. National wind energy associations in other countries probably have sections on small wind turbines.

A number of designs were developed by architects, inventors, and even people selling wind systems (most not built or tested) to integrate wind turbines into building structures in urban areas. The designs usually touted the increase of wind speed caused by the building. However, in the real world, incorporating wind turbines into buildings is a difficult choice because of noise, vibration, and safety concerns. In some concepts of installations on buildings, the wind turbines must be mounted perpendicular to the predominant wind direction because the wind turbines are fixed in yaw.

According to Dutton et al., the estimated energy production is in the range of 1.7–5.0 TWh in the built environment (turbines in urban areas, turbines mounted on buildings, and turbines integrated into buildings) in the U.K. [11]. The technical feasibility and various configurations are also discussed. There is an Internet site for urban wind turbines [12]. Available downloads include the *European Urban Wind Turbine Catalogue; Urban Wind Turbines: Technology Review (*companion text to the European Union's *UWT Catalogue); Urban Wind Turbine Guidelines for Small Wind Turbines in the Built Environment*; and *Windy Cities: Wind Energy for the Urban Environment*. The wind turbine guidelines include images of wind flow over buildings and example projects.

A newspaper in Clearwater, Florida, installed a stacked Darrieus unit next to its building. The unit consisted of three Darrieus turbines, 4.5 m in diameter, 6 m tall, 4 kW each (Figure 9.4). Fortis mounted three wind turbines (5-m diameter, 2 kW rather than the nominal 5 kW) on a factory and office building and experienced a small problem with vibration at high wind speeds due to the flexibility of the roof. The Aeroturbine has a helical rotor mounted in a 1.8 × 3 m frame rated at 1 kW [13].

A building in Chicago mounted eight units horizontally on the roof (Figure 9.5), although other buildings mounted units vertically. Two 6-kW wind turbines mounted on the roof of a civic center in the U.K. were described in a case study [14]. A different concept is mounting a number of small wind turbines on the parapets of urban and suburban buildings. The horizontal axis wind turbine had a rated power of 1 kW and was mounted in a modular housing measuring approximately 1.2 × 1.2 m. Fourteen wind turbines installed on a corner of the Energy Adventure Aquarium building (Figure 9.6) in California constitute a kinetic sculpture.

FIGURE 9.4 Three-stacked wind turbines (Darrieus), 4 kW each, next to building. Notice the vman on top. (Photo courtesy of Coy Harris, American Windmill Museum.)

FIGURE 9.5 Eight helical wind turbines, 1 kW each, horizontal axis, on top of building. (Photos courtesy of Kurt Holtz, Lucid Dream Productions.)

The most spectacular structure featuring integrated large wind turbines is the Bahrain World Trade Center. The two 240-m towers with sail silhouettes have three cross bridges that carry wind turbines. The turbines are 29 m in diameter, rated at 225 kW, and are predicted to generate around 1,100–1,300 MWh/year—11–15% of the energy needed by the buildings. The aerodynamic design of the towers funnels the prevailing onshore Persian Gulf breezes into the paths of the wind turbines.

FIGURE 9.6 Twelve 1-kW wind turbines mounted on parapet of building. (Photo courtesy of AeroVironment.)

9.1.1 Noise

Although zoning is an institutional issue, the regulations will affect the potential for erecting small wind turbines and may specify turbine size, tower height, required space surrounding the tower, noise restrictions, and even visual concerns of neighbors. The noise from a small wind turbine is around the level of noise in an office or in a home. Noise from a small wind turbine is rarely a problem because the level drops by a factor of 4 at a distance of 15 m, and is generally masked by background noise.

A sound study with a 10-kW wind turbine (wind speeds at 9–11 m/s) showed levels of 49–46 dBA for the running turbine and at a distance of 15 m from the turbine, respectively. Essentially no difference was found at distances of 30 m and more. However, if a wind turbine rotor is downwind, some sound is made every time the blade passes the tower. Even if the sound is at the same level as background noise, it can be annoying. In California, noise from a wind turbine must not exceed 60 dBA at the closest inhabited building.

9.1.2 Visual Impact

The State of Vermont has a scoring system for possible adverse visual impacts of small wind turbines [15] from the vantage points of private property (neighbors' views) and public views (roads, recreation facilities, and natural areas). The considerations for neighbors' views are:

1. What is the position of the turbine in the view?
2. How far away is the turbine seen?
3. How prominent is the turbine?
4. Can the turbine be screened from view?

For public views, two additional factors must be considered:

5. Is the turbine seen from an important scenic or natural area?
6. What is the duration of the view?

Each factor is rated by a point system (Table 9.1), with a total of 12 points for the residential view and 18 for the public view. If the score (Table 9.2) is below the significant range, the wind turbine is unlikely to have a visual impact unless it is near or within a scenic view. The score is only a general indicator for visual impacts of small wind turbines. Wind turbines will be visible, at least from some viewpoints because they will tower above surrounding trees.

TABLE 9.1
Vermont System for Scoring Visual Impacts of Small Wind Turbines

	Neighbor View				Public View	
	1	2	3	4	5	6
Points	View Angle (°)	Distance (m)	Prominent	Screened	Vista	Duration (s)
0	>90	>900	Below Tree Tops	Complete	Degraded	0
1	0–45	450–900	At Horizon Line	Multiple Trees	Common	<15
2	50–60	150–450	Above Horizon Line	Single Tree, 1/2–2/3	Scenic	<30
3	60–90	<150	Above Tallest Mt	No Screening	Highly Scenic	>60

TABLE 9.2
Score Sheet for Determining Visual Impacts of Small Wind Turbines

	Score	
	Neighbor	Public
Negligible	0–3	0–3
Minimal	3–6	3–9
Moderate	6–9	9–14
Significant	9–12	14–18

In the Midwestern Plains of the United States that have few trees, small wind turbines are noticeable from 1–3 km—the same as trees around a farmhouse. Comparable structures such as cell phone towers, light towers at highway interchanges, radio towers, and towers for utility transmission lines have comparable heights. The difference is that those towers do not have moving rotors.

9.2 WIND FARMS

Long-term wind data are critical for siting wind farms. Data should be collected at a potential site for 2–3 years, after which other questions arise. What is the long-term annual variability? How well can we predict the energy production for a wind farm? The siting of turbines over an area the size of a wind farm, about 5–20 km^2 is termed micrositing. The turbines should be located within a wind farm to maximize annual energy production and yield the largest financial return. Array losses have to be considered in the siting process.

In general, there will be a number of landowners and a developer who will lease an amount of land based on 20 hectares (ha) or 50 acres/MW of planned production. Not all the land will be used for turbines, and in many cases, developers lease land for further expansion. Actual values after construction will be from 12 to 18 ha/MW. Negotiation with a large number of landowners can present some difficulties, for example, one lease of 1640 ha involved 120 landowners.

9.2.1 Long-Term Reference Stations

To determine whether historical data from a site are adequate to describe long-term wind resources at another site, a rigorous analysis should be done. Simon and Gates [16] recommend that the annual hourly linear correlation coefficient be at least 0.90 between the reference site and off-site data. Remember to consider wind shear if the heights are different at the two locations. If the two sites do not exhibit similar wind speed and direction trends and lack similar topographic exposures, they will probably not have sufficient correlation value.

Long-term reference stations should be considered at all locations with wind power potential everywhere in the world. These stations should continue to collect data even after a wind farm is installed. The data will improve siting of wind farms and also provide reference sites for delineating wind resources for single or distributed wind turbines in the region. Wind turbine sizes have increased and hub heights are higher. Because wind speed increases with height in most locations, reference stations are needed to collect data at least at 50 m, and if possible to 100 m.

9.2.2 Siting for Wind Farms

The number of met stations and duration of data collection to predict the energy production for a wind farm vary depending on the terrain and the availability of long-term base data in the vicinity. In general, numerical models of wind flow will predict wind speeds to within 5% for relatively flat terrain and 10% for complex terrain, which means an error in energy of 15–30%. Therefore, a wind measurement program is imperative before a farm is installed. However, if a number of wind farms are already in the region, 1 year of data collection may suffice.

For complex terrain, one met station per three to five wind turbines may be needed. Because wind turbines for wind farms are now megawatt size, one met station per two wind turbines may be required in complex terrain. For somewhat homogeneous terrain as in the U.S. Plains, a primary tall met station and one to four smaller met stations may suffice. The tallest met station should be installed at a representative location, not at the best point of a wind farm.

Contour maps are used for locations of wind turbine pads and roads. In general, the wind turbines will be located at higher elevations within the wind farm area. The U.S. Geological Survey has topographical maps that can be downloaded. Topozone (now a subscription service) has interactive U.S. topography maps (at different scales) available online [17]. These maps are very useful for selecting met tower locations, micrositing, roads, and other physical aspects of wind farms.

The key factors for array siting for the Zond wind farms [18] in Tehachapi Pass were an extensive anemometer data network, the addition of new stations during the planning period, a timeframe of 1 year to refine the array plans, a project team approach to evaluate the merits of siting strategies, and the use of initial operating results to refine the rest of the array. A large number of met stations were needed because the spatial variation of wind resources over short distances on a complex terrain was greater than expected. The energy output from 2 projects consisting of 98 wind turbines and 342 wind turbines was within 3% of the predicted value. This experience shows it is possible to estimate long-term production from a wind plant with acceptable accuracy for the financial community. One of the key factors was an extensive network of met towers.

The money spent on micrositing is a small fraction of project cost, but the value of the information gained is critical for estimating energy production accurately. Many problems with low energy production are the results of poor siting.

Wind turbines have become larger, with rotor diameters from 60 to 150 m and hub heights of 60–100 m and even higher. Very little data show conditions above these heights, but NREL had a program for tall tower data [19]. One problem is that all tower data collected by wind farm developers are proprietary.

Because of wind shear, wind turbines are located at higher elevations on rolling terrain and mesas and on ridges on complex terrain. In the past, turbulence was considered a big problem for siting at the edges of mesas and ridges. However, taller towers allow placement of wind turbines on the edges that are perpendicular to the predominant wind direction. Consider wind turbines on mesas in Texas. The north edge of the mesa would have increased winds from northern storms in the winter due to the rise in elevation. The southern winds in summers allow room for expansion of the wake. Turbulence data for these sites are proprietary, primarily because turbulence affects operation and maintenance.

9.3 DIGITAL MAPS

Digital maps are useful as they give a general overview of wind resource, provide confidence in the data, and provide information about land use and transmission lines, and other features can easily be displayed on the same maps. NREL created higher resolution digital wind maps using terrain enhancement, mesoscale modeling, and geographic information systems (GIS). Again note that the maps are available through EERE, WINDExchange [1].

Wind Site Assessment Dashboard (formerly Windnavigator), a web platform based on Google Maps, is an interactive tool that includes wind resource maps and world data [20]. The map (200-m resolution) provides wind speeds at custom height of 10–140 m and a pointer to locate minimum and maximum mean annual wind speeds. Wind statistics including Weibull values and wind roses, and monthly and diurnal distributions are available. Selectable area maps at 200-m resolution (PDF or GIS data sets) can be purchased. Satellite, hybrid, and terrain views are available for the entire world. The Small windExplorer interactive map is available to the public online [21]. Mean wind speed data for heights of 24.4 m (80 ft), 30.5 m (100 ft), and 36.7 m (120 ft) are available.

A similar interactive wind resource map (map, satellite, hybrid, and terrain views) and data for much of the world, are available [22]. FirstLook, has wind speed data for 20, 50, and 80 m and with Wind GIS Data Layers, resolution is at 90 m. In addition, a solar resource map and prospecting tools are available. Remember, wind speed maps are useful indicators of wind energy and wind power maps are the next step.

9.4 GEOGRAPHIC INFORMATION SYSTEMS

A geographic information system (GIS) is a computer system capable of holding and using spatially oriented data. A GIS typically links different data sets or it displays a base set over which overlays of other data sets are placed. Information is linked as it relates to the same geographical area. A GIS is an analysis tool, not simply a computer system for making maps.

The two general bases of representing data are raster and vector. In raster-based data, every pixel has a value. Vector-based data are represented mathematically—endpoints for lines and lines for polygons. Each pixel can represent an attribute and the number of attributes depends on the number of bits: 16–256 colors or shades of gray. Therefore, pixels and vectors can have different attributes and are linked to a database that may be queried. A GIS allows a user to associate information with a feature on a map and create relationships that can determine the feasibilities of various locations, for example, a hierarchical system for locating anemometer stations for wind prospecting.

An overlay is a new map with specific features placed on top of a base map. An overlay is one form of a database query function. The overlay and base maps can be raster or vector images. The number of overlays is generally limited only by the amount of information that can be presented with clarity.

The main types of terrain data are the Digital Elevation Model (DEM) and the Digital Line Graph (DLG). They are available at different scales, for example, the DLG at 1:2,000,000, 1:100,000, and 1:24,000. Depending on the scale, the DLG data show highways, roads (even trails), lakes and streams, gas and utility transmission lines, and other features. The problem is that the data may have been taken from fairly old maps and may be incomplete. The DEM shows terrain height to 1 m on a latitude–longitude grid with a resolution of 3 arc seconds [pixels around 90 m $\times$ 90 $\times$ cos (latitude) m]. NREL coupled the DEM database with software to produce shaded relief maps of $1° \times 1°$.

A technique of terrain enhancement [23] was used to identify windy areas in the Midwest. In the flat or rolling terrain found in most of the Midwest, the two most important factors influencing wind speed are terrain elevation and surface roughness. The wind map (normalized from the PNL digital map) was adjusted to an average elevation and average surface roughness in a circle (12-km radius) around that point. The U.S. Geological Service Terrain Elevation Data was the base map consisting of average elevations in 1-km^2 grid cells rounded to the nearest 6 m. Terrain exposure was determined by subtracting actual elevation from the average elevation for each 1 × 1-km grid cell. Then a power correction factor was calculated by

$$\frac{P}{P_a} = \frac{\left(\mathrm{In}\left[\dfrac{H_h + E}{z_o}\right]\right)^3}{\left(\mathrm{In}\left[\dfrac{H_h}{z_o}\right]\right)^3} \tag{9.1}$$

where:

P_a = average power/area from normalized wind map
H_h = hub height, 50 m
E = exposure, m
z_o = roughness length (crop land, 0.03 m; crop land and mixed woodland, 0.1–0.3 m; forest, 0.8–1.0 m

Care must be taken when using P_a. Do you use the bottom or the middle of the wind class? Do you limit the number of wind class changes to one, especially for mountainous terrain?

9.5 WIND RESOURCE SCREENING

As an example, wind resource screening for the Texas Panhandle is presented [24,25]. The DEM (3 arc seconds resolution) and DLG data were used. The original DEM data were in blocks of 1° × 1°. Data for utility transmission lines (69 kW and higher) were input by hand. Two GIS systems (IDRISI and PC ARC INFO) for personal computers were used. IDRISI has built-in functions that enhance its use for wind resource screening: slope, hill shading, aspect, and orthographic projection. A data sheet showing bin sizes, maximums, and minimums accompanies these functions.

The Panhandle of Texas is part of the Southern High Plains, with rolling hills in the East and flat plains above the caprock. The elevation rises from 450 m in the Southeast to 1,460 m in the Northwest. The Canadian River goes from west to east across the Panhandle. The other notable feature is Palo Duro Canyon. The graphs can be viewed in color or gray scale, with up to 256 colors selectable.

At 256 colors, a DEM map for the entire Texas Panhandle would display contours 4 m apart. The base map (Figure 9.7) is the DEM data for the Panhandle. Most of the images were created using

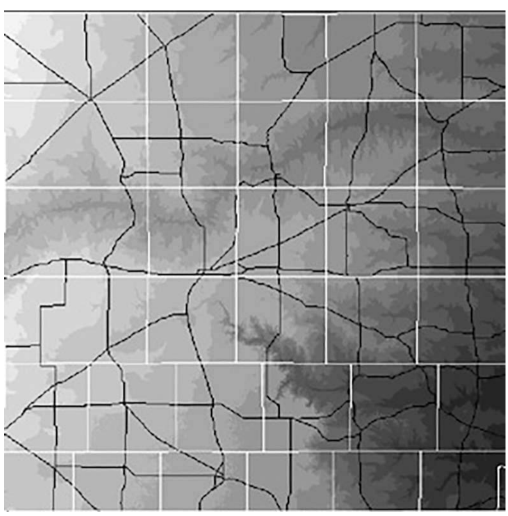

FIGURE 9.7 Digital elevation map (16 shades) of Texas Panhandle showing county boundaries and major highways. Contour lines are 62 m apart.

FIGURE 9.8 Terrain exposure from the average elevation for the Texas Panhandle showing major highways and transmission lines. Light areas have better exposure (range of 16 levels from −195 m to + 168 m).

16 values. The elevation data of the base map can be analyzed by various commands in IDRISI. Instead of the whole area, subsets of the data can be analyzed in the same manner to view more detail. Resolution is limited by the cell size of the original data.

The Panhandle has a large wind energy potential because it has class 3 and 4 winds over the whole area. On the flat open plains covering much of the Panhandle, almost 100% will fall into the same wind power class. In this region, wind speed increases with height; therefore, modest elevation may increase wind power dramatically. Terrain exposure affects areas above and below the average elevation. A 15-km radius was used to determine average elevation and the maximum change from this average was 190 m (Figure 9.8). An orthographic projection with an overlay of terrain elevation shows more clearly the areas of higher elevation. On the basis of terrain exposure, a revised wind map was calculated. Some of the regions with positive exposure were put into a higher wind class by this process and low areas were assigned a lower wind class.

GIS was used to screen wind resources based on the criteria of wind power class, terrain type, proximity to transmission line, slope, and aspect. Within these criteria, classes or levels can be selected to exclude or limit an area's suitability for wind plants. A map was generated for the following screening parameters:

- Wind class 3 and above
- Slope of 0 to 3 degrees
- Aspect from 155 to 245° for area where slope exceeds 1°
- Multiples of 8 km from transmission line (69 kV and above)
- Excluded lands: parks, roads, urban, lakes, wildlife refuges

The maps were combined to generate a map of the possible areas for wind farms by wind class. Within 8 km of transmission lines, the total area was 28,600 km^2—around 37% of the land in the Panhandle.

9.5.1 Estimated Texas Wind Power (Pacific Northwest Laboratory)

The Pacific Northwest Laboratory (PNL) estimated the capturable wind power for Texas at 50-m height as 134,000 MW from class 3 and above winds and 28,000 MW for the class 4 winds that blow primarily in the Panhandle. The PNL estimate was based on treating total power intercepted over a given land area as a function of the number of wind turbines, rotor swept area, and available power in the wind. Environmentally sensitive lands, urban areas, and terrains in valleys and canyons were excluded. The following formula was used to calculate the power intercepted by the rotor areas of wind turbines:

$$P_i = P_a A_t N \tag{9.2}$$

where P_a = average wind power potential (W/m^2); A_t = rotor area ($\pi D^2/4$); D = rotor diameter (m); and N = number of wind turbines. The calculation for the number of turbines that can be placed on a land area is:

$$N = \frac{A_i}{S_r S_c} \tag{9.3}$$

where A_i = land area; S_r = spacing between turbine rows (D); and S_c = spacing within turbine row (D m^2). Note that $S_r S_c$ is the land area devoted to one turbine. In general, wind plants only remove 3–10% of the land from other productive uses and most of the removed land is used for roads. Some wind farm roads are only 5 m wide. The roads at another wind farm with 3 MW wind turbines are over 10 m wide.

If the cost of land is high, the land area for a single wind turbine will be smaller; but the wind plant output will be lower due to array effects. In California, some wind plants have turbine spacing of 2D within the rows and 5D to 7D to the next row. As a general rule, in the Plains area, 5–12 MW can be installed per square kilometer (4D × 8D spacing). For the edges of bluffs and on ridges, 6–15 MW can be installed per linear kilometer (2D to 3D spacing, one row only). With closer array spacing the MW/km^2 would be larger and so would the array losses.

The average intercepted power can be calculated from Equation (9.2) or the intercepted power per unit land area can be calculated from:

$$\frac{P_i}{A_t} = \frac{nP_a}{4S_r S_c} \tag{9.4}$$

Remember, the calculation is for intercepted power, and capacity factors of 0.30–0.35 are used to estimate capturable wind power.

9.5.2 Estimated Texas Wind Power (Alternative Energy Institute)

The same procedures of terrain enhancement and GIS were used to estimate capturable wind power, also known as wind power potential, for Texas [26]. The selection criteria were class 3 or higher winds from a revised wind map showing terrain exposure, slope of 0–3°, and exclusion of urban areas, highways, federal and state parks, lakes, wildlife refuges, federal wetlands, and land within 15 km of transmission lines carrying 115 kV or more.

The capturable annual power was calculated for the wind turbines with 50 m hub height, 10D × 10D spacing, 30% capacity factor, and no array losses (reasonable for large spacing). With these assumptions, the estimated annual capturable wind power was 157,000 MW (525,000 MW of wind turbines at 30% efficiency) with an annual energy production of 1,300 TWh. These results are somewhat larger than the estimates determined by PNL.

The estimates were further revised with data (at 40 and 50 m) from Alternative Energy Institute (AEI) and private meteorological sites [27]. The estimates were then used to update the wind map (1-km pixel size) for Texas (Figure 9.9). Class 3 and 5 lands were reduced from the previous estimate and class 4 lands increased. The selection parameters were the same, except for slopes (0–10°) and areas within 16 km of electrical transmission line (≥ 69 kV) for usable land for wind power (Figure 9.10).

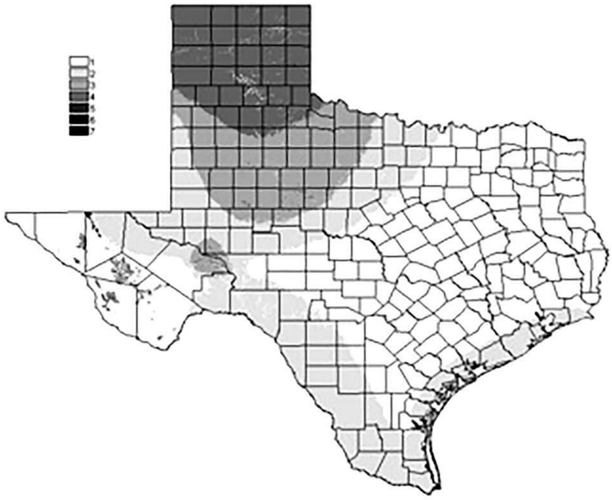

FIGURE 9.9 Texas wind power map, 1995.

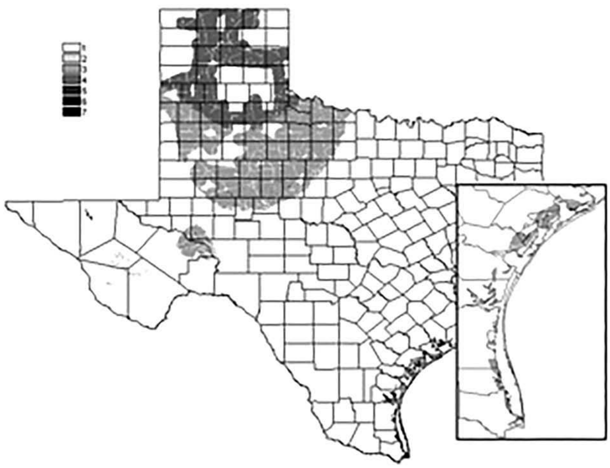

FIGURE 9.10 Texas land suitable for wind farms, 1995.

The estimate for capturable wind power (Table 9.3) is larger also because a spacing of 7D × 9D was used and the capacity factor was 30% for class 3 lands and 35% for class 4 and above lands. The estimates show the large wind potential, 172,000 MW (500,000 MW of installed capacity). However, only a fraction will be installed because the total electrical generating capacity of Texas was 120,000 MW (11,500 MW wind) in 2012. Maps and estimates are available from Kenneth Starcher, West Texas A&M University [28].

A number of wind farms have been built on mesas and terrain involving edges and bluffs. In one area of West Texas (Pecos, Upton, and Crockett Counties), 759 MW of wind farms were installed on mesas. Over 3,000 MW (installed from 2005 to 2009) in wind farms are sited along Interstate10 from Abilene to Roscoe and then northwest to Snyder along Highway 84. Some of these are on mesas with exposures from cliffs and bluffs on one side.

The limit of proximity to transmission lines has changed, and wind farms have been built within 40-km of major transmission lines. Also, the Texas Public Utility Commission promoted new

TABLE 9.3
Texas: Intercepted and Capturable Wind Power and Annual Energy Potential from Land That Satisfies the Screening Parameters

Wind Class	Area (km²)	Intercepted (MW)	Capturable Power (MW)	Energy (TWh/year)
3	62,299	302,365	90,170	795
4	41,391	232,196	81,269	712
5	42	288	101	1
6	54	471	165	1
7	2	22	8	
Total	110,788	535,342	172,252	1,509

transmission lines from West Texas and the Panhandle to connect with major load centers in the rest of the state. This will provide The Energy Reliability Council of Texas (ERCOT) a total of 18,000 MW of wind power—about 10,000 additional MW of wind capacity. Without the constraint of proximity to transmission lines, the estimate for the amount of intercepted wind power is 850,000 MW with capturable wind power around 270,000 MW. If offshore winds are included, the estimate will be even larger.

9.5.3 Wind Power for the United States

Similar estimates have been made for all the U.S. regions and states. Winds of class 4 and above [29] and access to transmission lines are the most common criteria. The *State Wind Working Group Handbook* contains articles and PowerPoint presentations by several authors [30].

9.6 NUMERICAL MODELS

Numerical models for predicting winds are becoming more accurate and useful, especially for areas of the world where surface wind data are scarce or unreliable. Models were derived from numerical models for weather prediction [31]. Remember that a small difference in wind speed can make a large difference in energy production. In the final analysis, surface wind data are still needed for wind farms.

MesoMap: This system was developed specifically for near-surface wind forecasting. It is a modified version of the Mesocale Atmospheric Simulation System (MASS) weather model. MesoMap uses historical atmospheric data spanning 20 years and a fine grid (typically 1–5 km). It simulates sea breezes, mountain winds, low-level jets, changing wind shear due to solar heating of the Earth's surface, effects of temperature inversions, and other meteorological phenomena. MesoMap does not depend on surface wind measurements although surface measurements are desirable for calibration.

The model provides descriptive statistics utilizing wind speed histograms, Weibull frequency parameters, turbulence and maximum gusts, maps of wind energy potential within specific geographical regions, and even the annual energy production data for wind turbines of any height for selected sites in a region.

WAsP: The Wind Atlas Analysis and Application Program software was developed by Denmark's Risoe National Laboratory to predict wind climate and power production from wind turbines. The predictions are based on wind data measured at stations in the region. The program includes a complex terrain flow model. WAsP was used to develop the European wind map (Figure 4.3) and is used by other governments and organizations across the world. Other models are available from links listed at the end of this chapter and elsewhere on the Internet.

9.7 MICROSITING

Wind maps, data compiled by meteorological towers, models, and other criteria are used to select wind farm locations. Other considerations for a wind farm developer are the type of terrain (complex to flat plain), wind shear, wind direction, and spacing of turbines based on predominant wind direction and availability, land cost, and requirements such as roads, turbine foundations, and substations. Terrain may be classified as complex, mesa, rolling, or plain. Passes may be classified as one type or a combination. Spacing is generally stated as diameter D of a wind turbine, so larger turbines will be farther apart.

As turbines have become larger, are wind shear data from 25 to 50 m sufficient to predict wind speeds at 70–100 m heights? The first answer is yes, for those parameters, but it is not definitive if the inquiry concerns another location in the same region.

In complex terrain, such as mountains and ridges, micrositing is very important. On flat plains, the primary consideration is spacing between turbines in a row and spacing between rows. On mesas, the highest wind speed is on the edge of the mesa facing the predominant wind direction so turbines may be set in a single row. In rolling terrains such as hills, wind turbines should be placed at higher elevations.

In California, the high wind classes arise from the rise of hot desert air and cooler air from the sea traveling through the passes. California has complex terrain at Tehachapi Pass, rolling terrain at Altamont Pass (east of San Francisco), and both ridges and flat terrain at San Gorgonio Pass near Palm Springs. The winds in the passes are predominantly from the west, so the turbine rows are primarily sited north–south. At San Gorgonio Pass, some wind turbines in rows were only 2D apart and rows were spaced 4D to 5D apart because of the high cost of leasing land. Where space is tight, turbines can be placed at different heights. As expected, the array losses are fairly large. Starting in 1998, smaller turbines were replaced with larger ones.

The wind farm near White Deer, Texas, has 80 1 MW wind turbines of 56-m diameter. The wind turbines have 4D spacing within rows and 15D between rows (Figure 9.11). North is at the top of the figure and the lines indicate roads at 1 mile (1.6 km). The buffer zone on the west is because the adjacent land was not under lease to the wind farm. Predominant winds are south–southwest during the spring and summer and from the north in winter. As lower winds occur in July and August, the rows are situated perpendicular to those predominant winds. The low spots are playa lakes that contain water only after rain so no turbines were installed in those locations. Only the west side of the wind farm is visible in the photo; there are more turbines to the east. Examples of wind farms in other terrain are shown in Figures 9.12–9.14. Figure 9.15 shows an offshore wind farm for comparison.

The amount of land taken out of production depends primarily on the lengths and widths of wind farm roads. Values vary from 0.5 to 2 ha per turbine. If county roads exist, the developer will use less land; however, the developer may have to improve the county roads to handle heavier traffic. Roads may be very expensive for a wind farm on a mountain ridge. The access road from the bottom to the top of the Texas Wind Project in the Delaware Mountains cost $1 million in 1993.

FIGURE 9.11 West side of a wind farm in the plains near White Deer, Texas. White lines are roads to show one square mile, which is equal to 260 ha. (Photo courtesy of Cielo Wind Power.)

FIGURE 9.12 Wind farm in rolling terrain, Lake Benton, Minnesota. (Photo courtesy of Wade Wiechmann.)

FIGURE 9.13 Wind farm on Southwest Mesa, near McCamey, Texas. Example of mesa with one row. (Photo courtesy of Cielo Wind Power.)

Civil engineering aspects of a wind farm site include location of assembly area and construction of electrical substation and roads (length, width, and grade over complex terrain). Roads must allow wide turns by trucks hauling the long blades. Many sites erect batch cement plants on-site, especially for construction on complex terrains of ridges and mesas.

A general rule of thumb is that around 5–10 MW/km^2 can be installed on land suitable for wind farms. However, on ridge lines at 2D to 3D spacing, the value would be around 8–12 MW per linear km. The kilometer measure is linear and the ridge is assumed to be more or less perpendicular to the predominant wind flow. As wind turbines become larger, the megawatts per square or linear kilometer will increase due to the energy output increase as the square of the radius. Most landowners lease blocks or areas of land, not just the places where turbines will be located. It was interesting in the Texas Wind Power Project that land leased for the wind farm included all land

FIGURE 9.14 Wind farm in complex terrain, Northwest Spain.

FIGURE 9.15 Nysted wind farm in Baltic Sea, Denmark. (Photo courtesy of Siemens.)

at the 1,453-m contour and above (elevation of ridges is 1,830 m). The landowner is now trying to determine whether land below the contour has any wind potential.

Satellite and aerial images are used in micrositing and are available from various sources; some are free. Flash Earth (www.flashearth.com) has the option of switching among sources, such as Google Maps, Microsoft VE, and others. The wind farms in the images are fairly distinct, primarily because of the roads at the sites and the areas around the wind turbines. Oil fields show the same pattern, but the roads are not as wide.

In some farming areas, round circles for irrigation sprinklers are very prominent; large circles represent section sprinklers (1 square mile, 260 ha), and small circles represent quarter-section sprinklers. The shadows of the wind turbines are more obvious than the wind turbines, and the angle of a shadow may be different from one part of the wind farm to an adjacent part because the images were taken at different dates and times. Images from different sources will also be taken at different dates and times. New wind farms will not appear in satellite images until the images are updated—more than a year may elapse between updates.

Micrositing techniques of wind farm developers are proprietary. However, satellite images show the layout of wind farms, and good information about siting may be obtained from the images and topographic maps. If the type and model of a wind turbine are known, the spacing can be

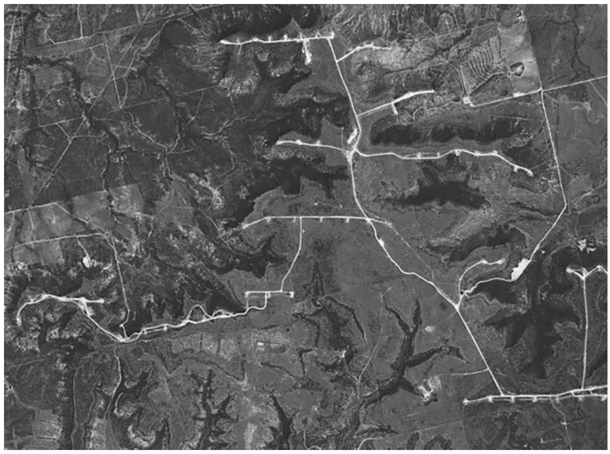

FIGURE 9.16 Satellite image of west side of Trent Mesa wind farm, Texas.

estimated from an image. The image of Trent Mesa, Texas (Figure 9.16) shows about half the layout of the wind farm that contains 100 wind turbines, 66 m in diameter, rated at 1.5 MW.

Economic and institutional issues also affect micrositing. An example is the Waubra wind farm project (192 MW) in Australia [32], which involves environmental, cultural, heritage, and environmental management issues. Since installation, many residents have expressed opposition, claiming health effects caused by wind turbines. One vocal landowner was bought out by the wind farm.

9.8 OCEAN WINDS

Ocean wind observations (see Section 4.4) provide complementary sources of information for siting of offshore wind farms. The advantages of ocean wind maps are:

- Some satellite wind maps are public domain.
- All offer global coverage allowing observation of large areas without large numbers of meteorological towers.
- All are accessible in archives spanning several years.
- Accuracy is sufficient for wind resource screening.
- They quantify spatial variations.
- They are available at resolutions of 400 m, 1.6 m, and 0.25 degree.
- Software has been developed for their use.

The major problems with ocean winds are:

- Data are for 10 m height and values of wind shear are not known.
- Standard deviations are around 1.2 to 1.5 m/s on mean wind speed.
- Data are not available or not as reliable within 25 km of shore.

Ocean winds were used for wind resource estimation for Denmark [33]. Weibull parameters were calculated from the wind speed data to determine a wind speed distribution from which wind energy production could be estimated.

The average wind speed for Padre Island, a barrier island off Corpus Christi, Texas, is 5.1 m/s at 10-m height—the same value as ocean winds 25 km from the coast. Data from 10- to 40-m height indicated an annual average shear exponent of 0.19. A shear exponent of 0.15 was noted for a site 15 km off Cape Cod, Massachusetts [34]. Also, ocean winds, terrain, and predominant wind direction will indicate regions of wind potential for islands and near shores. For example, ocean winds indicate excellent wind resources for the islands of Aruba, Bonaire, and Curaçao off the northern coast of Venezuela.

9.9 SUMMARY

GIS provides very flexible and powerful tools for terrain analysis relevant to wind energy prospecting. They can help reclassify existing wind maps and identify areas showing potential as possible wind farm sites. In addition, GIS can be used to quantify wind power potential and, in conjunction with numerical models, estimate annual energy production.

After a location is selected, GIS and topographical maps can be used for micrositing. Wind turbines should be located within a wind plant area to maximize annual energy production. However, the normal 90-m resolution may not be detailed enough for micrositing on complex terrain. PNL used a technique of spline interpolation to develop a finer grid from the 90-m data. Of course, if the DEM data at 10-m resolution are available, interpolation is not needed.

A number of numerical models for micrositing are available and most run on personal computers. More powerful programs for weather forecasting and micrositing, which run on large computers or clusters of PCs, are also available. In general, these must be purchased.

PROBLEMS

1. A building is 20 m long, 15 m wide, and 15 m tall. You want to install a 10-kW wind turbine. How tall a tower will you need and how far away from the building should you place it?
2. Several trees 20–30 m tall are near a house. You want to install a 10-kW wind turbine. What is the minimum height of the tower? What is the approximate cost of the tower?
3. Refer to Figure 9.3. The building is 15 m tall. What is the power reduction at 15-m height at a distance of 60-m downwind? At 150-m downwind? Would it be cheaper to use a taller tower or to move the tower farther away from the building? Show all cost estimates.
4. Is there a small wind turbine in your region? If yes, what are the visual impacts from the neighbor's view and from the public view? Use Tables 9.1 and 9.2 to estimate scores.
5. Using Equation (9.1), calculate the corrected power for a class 3 wind area if the terrain exposure is 80 m and area is grassland. Use the bottom and middle values for class 3.
6. Estimate the annual energy production for a 50-MW wind plant where the average wind power potential is 500 W/m^2 at 50-m height. Select the size of turbine from commercial turbines available today.
7. Do Problem 6. The land is now high priced. Select close spacing and estimate array losses.
8. What land area must you lease for a 50-MW wind farm? Select the size of turbine from commercial turbines available today and calculate spacing. Remember, spacing your turbines too closely will cause array losses. How many megawatts can you install per square kilometer?
9. Array spacing is $4D \times 8D$, for a 3-MW wind turbine 90 m in diameter. How many can be placed in a square kilometer?
10. The row spacing for 3-MW turbines 90 m in diameter is 2D. How many can be placed per linear kilometer on a ridge?
11. Assume you have complex terrain. What size of land area must you lease for a 50-MW wind farm? Select the size of turbine from commercial turbines available today and calculate the spacing. How many megawatts can you install per square kilometer?
12. In your opinion, what are some advantages and disadvantages of using vector- or raster-based GIS to determine wind energy potential?
13. Check two of the links on numerical models listed in the Links section of this chapter. See whether they contain examples of wind maps. List the website chosen, geographical region of wind map, and map resolution.

14. For the White Deer wind farm (Figure 9.11), what is the land area allocated for each turbine? How many turbines can be placed in a square kilometer?
15. For the White Deer wind farm (Figure 9.11), if the roads are 7 m wide, estimate the amount of land taken out of production for the wind turbines within the square mile shown in the figure. Do not forget the spaces between turbines.
16. Go to Zoom Earth (https://zoom.earth) and search for White Deer, Texas (latitude, N 35°, 27 min; longitude, W 101°s, 10 min). The wind farm is just northwest of the town. Zoom in to see the layout of the wind farm. Estimate the number of wind turbines per square mile for the farm. Remember, not all the land within the farm will have wind turbines on it.
17. Go to Google Earth (www.google.com/earth/) and search for the wind farms in San Gorgonio Pass, California, just northwest of Palm Springs. Estimate the spacing for one of the densely packed wind farms.
18. How many meteorological stations, at what height, and over what period are needed to determine the wind potential for a 50 MW or larger wind farm? In general, terrain will not be completely flat. Also remember wind turbines are getting larger, and thus, hub heights are larger. For your selection of number, height, instrumentation, and time period; estimate the costs for obtaining the data.
19. Go to www.remss.com and look at QSCAT data for area off Cape Cod during September 2007. Choose region "Atlantic, Tropical, North." What is the average wind speed and from what direction?
20. In a preliminary data collection for a wind farm, for how long should data be collected if: (a) no regional data are available; (b) good regional data are available; and (c) other wind farms are in the area.
21. Find a quadrangle map that shows Mesa Redonda (34.9157°N, 107.1337°W) in Quay County, New Mexico (www.newmexico.org/map). What is the elevation of the mesa? You can see all of the mesa in a 1:200,000 view. You will need a 1:50,000 view to read elevations. Can use Topoquest (www.topoquest.com) or Mapcarta (https://mapcarta.com)
22. What is the general rule for calculating megawatts per square kilometer (MW/km^2) in plains and rolling hills? What is the rule for calculating MW per linear km for ridges and narrow mesas?
23. From Table 9.3, estimate MW/km^2.
24. From Table 9.3, use the general rule for 8 MW/km^2, what is the maximum megawatts of wind that could be installed? What is the maximum capturable power?
25. What is the annual wind speed at 100-m height on Mesa Redonda, south of Tucumcari in eastern New Mexico?

LINKS

EMD, WindPro. www.emd.dk/WindPRO/Frontpage Environmental impacts and siting of wind projects, www.energy.gov/eere/wind/environmental-impacts-and-siting-wind-projects.

D.M. Heimiller and S.R. Haymes. 2001. *Geographic information systems in support of wind energy activities at NREL*. REL/CP-500-29164. www.osti.gov/bridge.

MesoMap. software, models. www.awstruewind.com.

EERE, WINDExchange https://windexchange.energy.gov

ReSoft software, models. www.resoft.co.uk/English/index.htm.

RETscreen, free software, decision-making tools. www.retscreen.net.

Trent Mesa Wind Project. www.trentmesa.com.

TRC, CAMET, and MM5 software, models. www.src.com/windenergy/windenergy_main.htm.

WAsP, software, models. www.wasp.dk.

WindFarmer, software, models. Now at DNV GL. www.dnvgl.com/services/windfarmer-3766.

Wind Logics, software, models. www.windlogics.com.

Wind Resource Assessment Handbook. www.nrel.gov/docs/legosti/fy97/22223.pdf.

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15. Public Service of Vermont. Siting a wind turbine on your property: Putting two good things together. http://publicservice.vermont.gov/sites/dps/files/documents/Renewable_Energy/Resources/Wind/psb_wind_siting_handbook.pdf.
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