# OROGRAPHY AND WIND TURBINE SITING

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"The wind in passing the summits of mountains becomes swift and dense and as it blows beyond the mountains it becomes thin and slow, like water that issues from a narrow channel into the wide sea."
Leonardo da Vinci (1452-1519)

## INTRODUCTION

Orography plays an important role in the siting of wind turbines. It determines whether there are capable of reaching their design lifetime or their early failure. It plays an important role in the screening, deflection and acceleration of the wind.

Obstacles such as ridges, hills and cliffs affect the wind velocity profile. Some patterns may be very favorable for producing wind power. Some other patterns must be strictly avoided since they can create considerable screening or turbulence.

## HEIGHT CONSIDERATION

It is not advisable to include the altitude of the terrain in wind shear calculations. As an example a good site for wind turbines is to position them atop a cliff along seashore. If the cliff is 10 meters or 30 feet in height, it would be incorrect to add the height of the cliff to the height of the structural tower in estimating the effective height of the nacelle.

Figure 1. Siting wind mills along a seashore behind a cliff escarpment. Source: Soren Krohn.

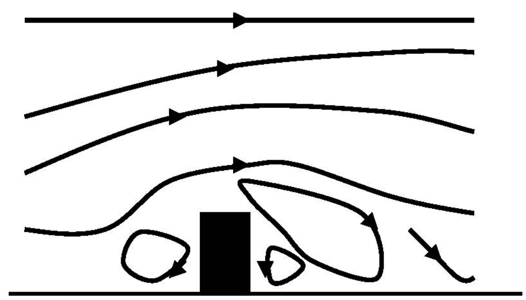
Upon close consideration, it can be noticed that the presence of the cliff would create turbulence, and would break the wind even before it reaches the cliff. This eliminates the possibility of positioning the turbines along the cliff close to the sea shore, since this would most likely lower the energy output, in addition to shortening the lifetimes of the turbines from the fatigue loading caused by the turbulence.

It may have been possible to locate the turbines near the shore only if there well a well-rounded hill that would have caused a wind speed up effect through the hill effect.

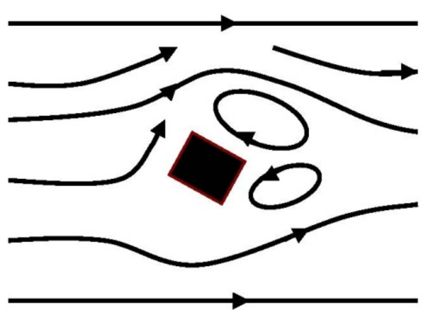
A better option is to position the wind turbines at a distance inland where the wind turbulence would have subsided leading to a smooth flow over the flat terrain. In this case the effective height used in the wind profile calculations would be the height above the flat terrain.

## EFFECT OF OBSTACLES

Obstacles to the wind such as buildings, trees, woods and forests, tree lines and rock formations can appreciably decrease the wind speed, in addition to creating turbulence.



Elevation view of wind flow around an obstacle.



Top view of wind flow around an obstacle.

Figure 2. Top and elevation view of wind flow around an obstacle.

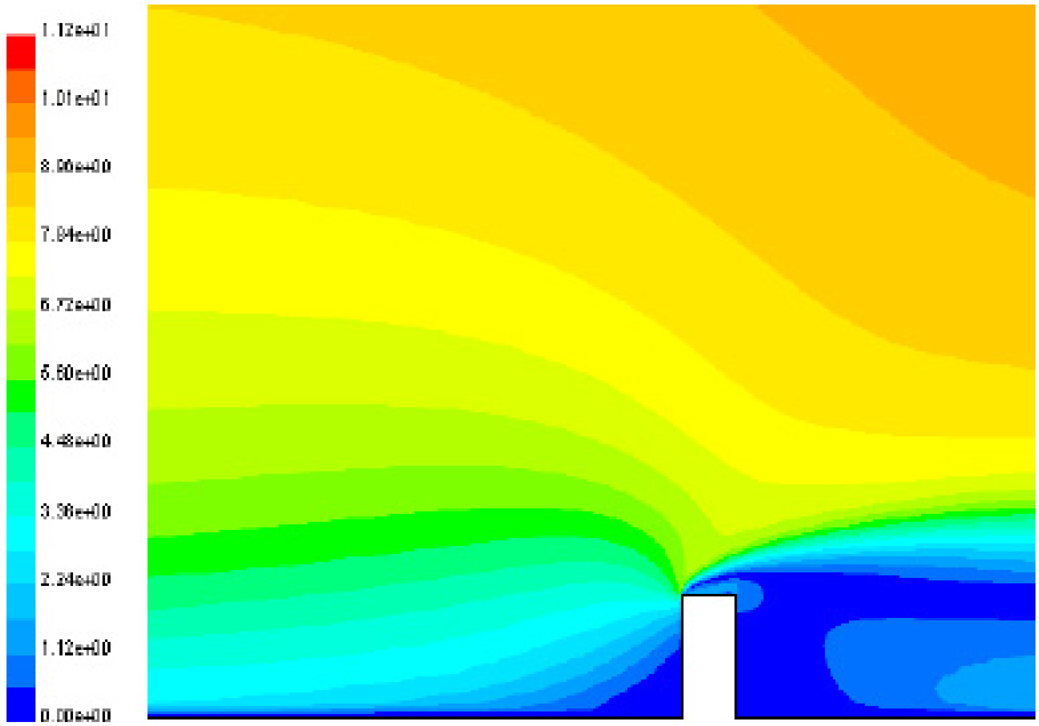



Figure 3. Velocity contours in meters per second around a building determined by computational fluid dynamics. The contours are affected way ahead and behind the obstacle.

The wind stream would flow around an obstacle intersecting its path creating a turbulence zone extending to about 3 times the diameter of the obstacle. The turbulence occurs primarily behind the obstacle, and to a lesser extent in front of it. Major obstacles must be strictly avoided in the siting of wind turbines, particularly if they are located upwind in the prevailing wind direction.

The decrease in wind speed due to an obstacle is proportional to the height and width of the obstacle. The effect is more pronounced close to the ground and nearer to the obstacle.

Obstacles are taken into account in the calculation of wind energy production at a given site if they are located at less than a kilometer from a wind turbine at the prevailing wind direction.

## OBSTACLES POROSITY

The decrease of wind speed behind an obstacle depends on its porosity. Deciduous trees in the winter will be more porous than in the summer. Porosity is defined as:

$$\text{Porosity } \alpha = \frac{\text{Open area of obstacle}}{\text{Total area facing the wind}}$$

A building is solid with zero porosity, while a fairly open deciduous tree with dropped leaves in the winter may have a porosity of one half, letting half the wind stream through it. In the summer with leaves on the tree, the porosity may be decreased to about one third.

## SHELTER EFFECT OR WIND SHADE POWER LOSS

Wind speed at the location of a turbine tower will be decreased by a blunt obstacle that is not well streamlined in the direction of the wind. Consider a zero porosity building, 20 meters in height and 60 meters in width positioned 300 meters from a 50 meters height at the hub wind turbine. At the hub height, the wind speed would be decreased by 3 percent to 97 percent of the wind speed without the obstacle.

This suggests a loss in the energy production from the wind turbine. Considering that the available power is proportional to the cube of the wind speed:

$$\frac{P}{P_0} = \left(\frac{V}{V_0}\right)^3 \tag{1}$$

The relative loss in power production caused by a decrease in wind speed is:

$$\frac{P_0 - P}{P_0} = 1 - \frac{P}{P_0} = 1 - \left(\frac{V}{V_0}\right)^3 \tag{2}$$

Substituting the data we get:

$$\begin{aligned}\frac{P_0 - P}{P_0} &= 1 - \left(\frac{0.97V_0}{V_0}\right)^3 \\ &= 1 - (0.97)^3 \\ &= 1 - 0.91267 \\ &= 0.0873 \\ &= 8.73\,\textit{percent}\end{aligned}$$

This amounts to 8.7 percent reduction in the power production from the wind turbine.

The factors affecting wind shade are:

1. **Wind turbine hub height:**

Wind shade will be less the higher the turbine hub is above the highest point of the obstacle. However, the wind shade can extend up to 5 times the height of the obstacle behind it.

**2. Separation distance:**

The shadow effect will decrease as we move away from the obstacle. In terrain with a low roughness such on water surface, the effect of the obstacles such as an island, may be measurable for up to 20 kilometers away from the obstacle.

**3. Roughness length and roughness class:**

Terrain with low roughness will allow the wind passing outside the obstacle to mix easily with the wake behind the obstacle, mitigating the effect of the wind shade.

A rule of thumb is that obstacles closer than 1,000 meters from the turbine are dealt with as individual obstacles in the prevailing wind direction. Otherwise obstacles are accounted for through the roughness class or roughness length.

**4: Obstacle height:**

The wind shade magnitude is directly proportional to the height of the obstacle. If the turbine is closer to the obstacle than 5 times the obstacle height, or if the obstacle is taller than the hub height, the shadow effect will depend on the exact geometry of the obstacle.

**5. Obstacle width:**

A narrow object will cast a smaller shadow than a wider one. Some calculation methods consider the obstacles as infinite in width. Other methods subdivide the horizon around the wind turbine in 30 degrees sectors.

**6. Obstacle porosity**

Trees with dropped leaves will cause less of a shadowing effect than buildings. Trees with dense foliage will cause an intermediate effect. The wind shade will be proportional to the solidity of the obstacle:

$$\begin{gathered} \text{Solidity} = 1 - \text{Porosity} \\ S = 1 - \alpha \end{gathered} \tag{3}$$

A building will have a solidity of unity or zero porosity. A group of buildings will have a porosity:

$$\alpha = \frac{\text{Area of open space}}{\text{Total area seen by turbine}}$$

## WAKE OR ARRAY EFFECT

In extracting power from the wind, the turbine brakes the wind stream, a wake of highly turbulent trail of slowed down wind is formed behind the turbine; much like the wake formed behind a ship.

In a wind farm arrangement, the wind turbines are placed at least three rotors diameters apart to avoid subjecting them to too much downstream turbulence from the wake of other turbines. In the prevailing wind direction, the turbines must be spaced even wider.

Figure 4. Wake effect from wind turbine shown with smoke generated at a single blade turbine rotor's tip. This turbine rotates clockwise, whereas most turbines rotate counterclockwise. Source: Risö National Laboratory, Denmark.

Figure 5. Effect of turbulence and wind wakes on ball bearings of a wind turbine gearbox. Source: NREL.

## PARK EFFECT AND TURBINES LAYOUT

To avoid the wake effect, wind turbines would ideally positioned as far as possible from each other. However, land use and the economics of connecting the turbines through cabling to the electrical grid, dictate that some optimal spacing must be sought.

As a rule of thumb, turbines in wind farms are spaced 5-9 rotor diameters apart in the prevailing wind direction, and 3-5 rotors diameters apart perpendicular to the prevailing wind direction.

In the figure showing the layout of a typical wind farm with 15 turbines, the turbines are spaced 7 rotor diameters apart in the prevailing wind direction, and 4 diameters apart in the perpendicular direction.

With consideration of the wind rose at a given location, the Weibull or Rayleigh wind probability density function and the terrain roughness in different directions, developers and manufacturers can estimate the power loss from the shading of the wind turbine on each other. The typical loss in power production is in the range of 5 percent.

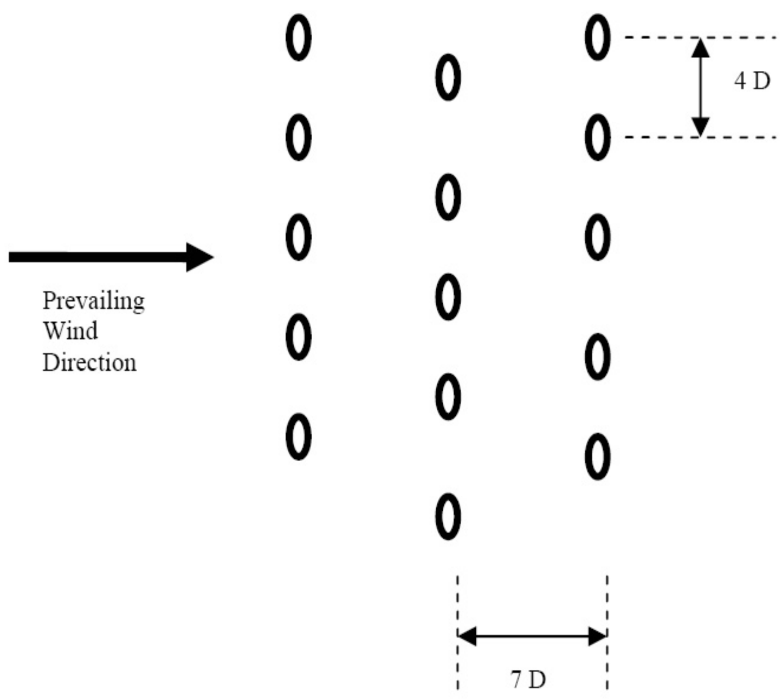



Figure 6. Typical turbines spacing in a wind farm in rotor diameters D.

## WAKE INTERFERENCE

Figure 7. Wake from offshore wind turbines at Horns rev west of Denmark. Photo: Vattenfall.

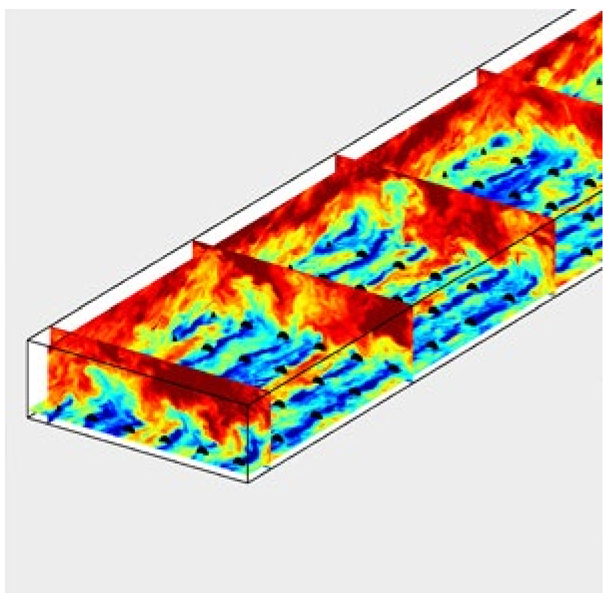


Figure 8. Wake interference in a wind farm [1].

Plans for wind farms with more than 1,000 turbines are under consideration. The economics of such wind farms depends on the accurate predictions of their power output, and it is far more difficult to model how such large wind farms will behave. Simulating the interactions between many wind turbines, in a range of different weather conditions, can be a complex proposition.

Poor data gathering and ineffective computer models meant that wind developers were prone to overestimating the energy production of their farms by over 10 percent, enough to destroy profits and in some cases prevent them from making loan repayments [1].

The construction of one proposed 1,000-turbine mega wind farm, the Chokecherry and Sierra Madre project at the Overland Trail ranch in Wyoming, is expected to begin next year. The project's developers have measured wind speed, direction, temperature, and other weather conditions at the site for five years, even though two years is the standard. They have gathered data from 32 meteorological towers that rise 60 to 80 meters above the ranch's rolling, sage-brush covered hills, along with measurements from sound-based radar or sodar that can scan the wind at altitudes up to 200 meters, the height of some wind turbines. As the wind moves through them, the turbines create wakes that can interfere with the performance of downstream turbines. The wind farm could generate at least 8.76 billion kilowatt hours a year, or enough power for 770,000 homes.

Current models is they do not accurately represent the variability of wind, not just at ground level, but even hundreds of meters above the level of wind turbines. Recent research suggests that in some weather conditions, models can dramatically underestimate wake losses. The wakes carry a lot further than previously estimatedin large wind farms with multiple rows, the longer wakes could affect many wind turbines, lowering their output.

Charles Meneveau, a professor of mechanical engineering at Johns Hopkins University, has developed models of the way very large wind farms disturb the air up to a kilometer above them. Based on some of his simulations, he has shown that turbines should actually be placed twice as far apart as they usually are to get the most out of the wind.

Turbulence, while it can be a problem, is also essential for large wind farms. Without any turbulence, the first rows of a wind farm would essentially block the wind, limiting the number of rows that could be installed. Turbulence actually pulls wind down from above the wind farm. As a result, the last row in a wind farm, while it gets somewhat less energy than the first row, can still generate electricity, as long as wind turbines are properly spaced. Turbines in the front row might be programmed to orient their blades to allow more wind to pass by them, thereby improving the performance of turbines in subsequent rows, and so increasing the output of the entire wind farm.

## TUNNEL SPEEDUP EFFECT

In a wall between tall buildings or through a narrow mountain pass, the air becomes compressed on the upstream side, and according to Bernoulli's equation the wind speed increases considerably between the obstacles to the wind.

According to Bernoulli's equation:

$$p_1 + \frac{1}{2}\rho V_1^2 = p_2 + \frac{1}{2}\rho V_2^2 = \text{constant} \tag{4}$$

From which:

$$V_2^2 = \frac{2}{\rho}(p_1 - p_2) + V_1^2 \tag{5}$$

If $p_1 > p_2$, then $V_2 > V_1$.

In addition, the continuity equation applies in between the open area with cross section $A_1$ and the cross section area of the tunnel $A_2$:

$$\rho A_1 V_1 = \rho A_2 V_2 \tag{6}$$

where we assume that the wind density did not change, thus:

$$V_1 = \frac{A_2}{A_1} V_2 \tag{7}$$

If $V_2 > V_1$, then $A_1 > A_2$. Thus the larger speed will correspond to the smaller constricted area.

Substituting for $V_1$ in Eqn. 5, we get:

$$V_2^2 = \frac{2}{\rho}(p_1 - p_2) + \left(\frac{A_2}{A_1}\right)_1^2 V_2^2 \tag{8}$$

Solving for $V_2$, we get:

$$V_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho\left[1 - \left(\frac{A_2}{A_1}\right)^2\right]}} \tag{9}$$

If we designate the constriction or contraction ratio for the tunnel as:

$$\beta = \frac{A_2}{A_1} < 1 \tag{10}$$

we can rewrite Eqn. 9 as:

$$V_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho\left[1 - \beta^2\right]}}, \beta = \frac{A_2}{A_1} < 1 \tag{11}$$

This equation is the basis for the design of wind tunnels.

The tunnel effect is noticeable in the constriction between the tall buildings in the city of Chicago along Lake Michigan in the USA. Accordingly, Chicago is affectionately known as “The Windy City” or “The Windy” in short.

The wind tunnel effect has been widely exploited in the state of California in the USA, where numerous wind farm locations were chosen at its mountain passes. For instance, if the wind speed in an open terrain were 6 m/sec, it could reach 9 m/sec in a natural tunnel such as a mountain pass. Placing a wind turbine in a natural tunnel is a smart way of obtaining higher wind speeds than in the surrounding terrain.

To get a good tunnel effect, the wind turbine should be embedded in the landscape. If the hills are uneven and rough, this could lead to turbulence shortening the design lifetime of the wind turbines. Multiple early failures were in fact observed in the California wind farms built within its mountain passes.

Figure 9. Siting wind parks in the mountain passes of California takes advantage of the tunnel effect.

## HILL SPEEDUP EFFECT

A common approach to site wind mills is to position them on hills and ridges overlooking the surrounding landscape. At these locations the wind turbines have a wide exposure to the prevailing winds from all directions.

In addition, on these hills and ridges it is observed that the wind speed is higher than in the surrounding landscape. This is due to the fact that the wind becomes compressed on the side of the hill facing the wind, and once it reaches the top and spills to the other side it can expand again in the low pressure area on the lee side of the hill.

The reduction in the static pressure is associated with an increase in the kinetic pressure in Bernoulli’s equation, and hence an increase in the wind speed results.

The wind upstream of the hill starts bending upwards before reaching the hill since the high pressure area extends to a distance upstream from the hill.

Once the wind passes through the rotor blades of the wind turbine it becomes highly irregular. This leads to turbulence if the hill has a non smooth uneven or irregular surface which would negate the advantage of a higher wind speed. It can even lead to damaging erosion on the lee side of the hill.

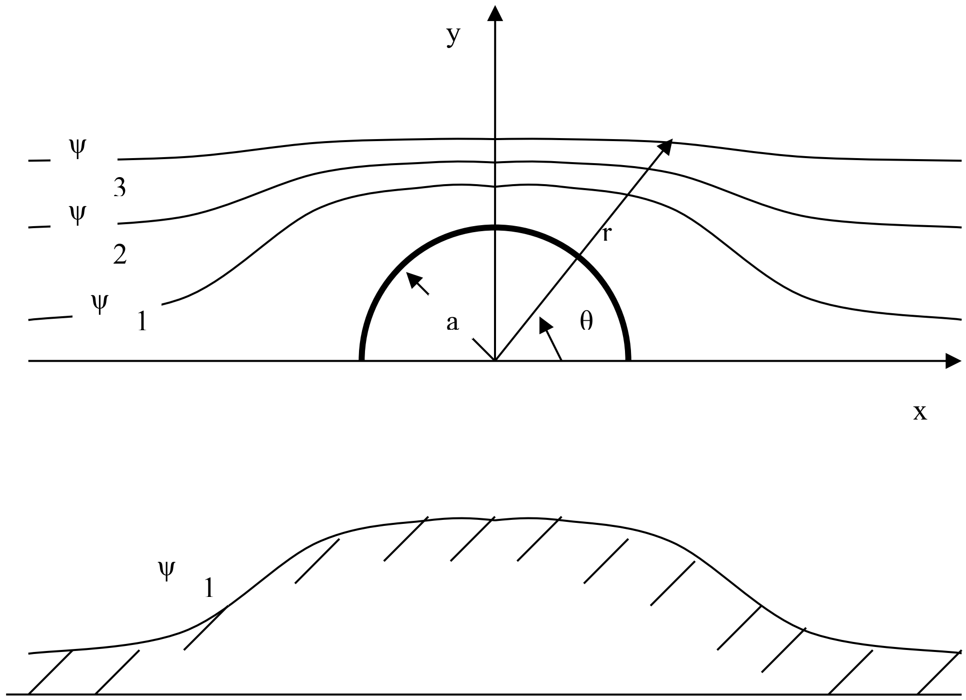



Figure 10. Streamlines of wind flow over ridges, hills and cliffs.

To estimate the hill speedup effect we consider the streamlines expressions in the polar coordinates (r, θ) for the two cases:

$$\psi_{\text{long ridges}}(r,\theta) = U\left(r - \frac{a^2}{r}\right)\sin\theta,$$

$$\psi_{\text{circular hills}}(r,\theta) = U\left(r^2 - \frac{a^3}{r}\right)\sin^2\theta, \qquad (12)$$

where: $U$ is the wind speed upstream from the obstacle

The distribution of velocity above the summits is given by the expressions:

$$V_{\text{long ridges}}(y) = U\left(1+\frac{a^2}{y^2}\right),$$

$$V_{\text{circular hills}}(y) = U\left(1+\frac{a^3}{2y^3}\right), \tag{13}$$

where: a is the radius of the generating cylinder or sphere
y is the height above the center O

It must be recognized that hills in the shape of hemispheres or hemi-cylinders do not occur. However, any streamline can be replaced by a solid surface of the same shape without affecting the results above it. If the shape of a ridge or a hill coincides with a streamline, the velocity can be calculated from the flow above it.

To take into account viscous forces, simulations in wind tunnels or the use computational fluid dynamics would give more detailed results.

## SITING WIND TURBINES

### INTRODUCTION

A suitable wind site can be identified by simple initial observations. The growth patterns of trees and shrubs can give important clues as to the prevailing wind direction.

Along rugged shorelines the pattern of erosion over centuries points out to the direction of the blowing wind.

### WIND CONDITIONS

Meteorology data ideally in the form of a local wind rose calculated over a 30 years period can be sought as a best guide. One must be careful, however that the meteorology data apply to a large area, and may not be reliable as planning tool for the particular locality of the projected wind farm.

If wind turbines already exist in the locality, their operational results would be the best guide to the local wind conditions.

### SOIL CONDITIONS

The feasibility of pouring suitable foundations for the turbines, and the access roads construction necessary for using heavy erection and maintenance equipment must be a consideration in a wind turbine project.

### LOCATION VIEW

A location with a wide and open view of the landscape would exploit the prevailing winds. Few obstacles and a low roughness of the terrain are desirable. Even more advantageous would be the presence of a smooth rounded hill site providing the hill speedup effect.

### METEOROLOGICAL DATA

Meteorological data is routinely collected at airports and weather forecasting sites. This can be used to assess the general wind conditions at a given site. However, accurate and detailed wind speeds measurements are not as important for these purposes as they are for wind power systems planning.

Wind speeds are influenced by surface roughness in the surrounding landscape, by obstacles such as tree lines, woods and forests, buildings and other objects in the landscape.

Accordingly wind calculations must be based on measurements or adjustments that are specific to the projected site. Directly using the meteorology data which are of low resolution and are averages over large areas without adjustments to the particular site, will generally underestimate the true wind energy potential of a local site.

## ONSHORE WIND FARM SITES

### KING MOUNTAIN WIND FARM, TEXAS, USA

Figure 11. King Mountain wind Farm, Texas, USA takes advantage of the hill effect..

This wind farm was co-developed by Renewable Energy Systems Inc. (RES), an international company based in the UK and owned by Florida Power and Light (FPL). RES acted as the Engineering, procurement and Construction (EPC) contractor. It was constructed over the period March to December 2001. Several power purchase agreements exist: 198.9 MW with Reliant Energy, 76.7 MW with Austin Energy, and 2.6 MW with TNWP.

It is composed of 214 Siemens SWT-1.3-62 (Initially: Bonus, Active Stall) turbines with a rating of 1.3 MW for a total capacity of 278.2 MW and annual potential energy production of 750 GW.hr.

The 214 wind turbines connect to the power grid network via 4 85 MVA primary substations.

It is located in Upton County in West Texas. The turbines are sited in rows along the south eastern and north western edges of a mesa surrounded by deep ravines. The turbines are positioned in rows of up to 56 turbines with 2.5 rotor diameters spacing.

The location subjects the turbines to a dust, sand and high temperature environment. The design of the turbines was modified for the desert like environment with sufficient cooling of the components and protection with seals and filters against the intrusion of wind-blown sand.

## TOMAMAE GREENHILL WIND FARM, JAPAN

Figure 12. Tomamae Greenhill wind farm, Japan.

The developer is the Tomen Corporation under challenging climatic conditions with a high incidence of lightning strikes, occasional typhoons and cold winters with access to the turbines prevented by heavy snow.

The turbine were sited on ridges along the 2 kms long site. The project was constructed from August to December 1999, consisting of 20 1 MW units of Siemens SWT-1.0-54 for a total rated power of 20 MW.

## RAVENSBURG KREMPIN WIND FARM, GERMANY

Figure 13. The Ravensburg Krempin wind farm, Germany.

This wind farm was built over the period July to September 1999 in Bad Doberan at Meckelenburg in Western Pomerania, Germany. It is located within 10-12 kms from the Baltic Sea. At locations near Krempin, Karin, Kamin and Ravensburg, 12 units of the Siemens SWT-1.3-62 1.3 MW of rated power were constructed with a total capacity of 15.6 MW.

**SMOLA WIND FARM, NORWAY**

Figure 14. Smolia Wind Farm at Trondheim, Norway.

The developer of Norway's first wind farm was Statkraft SF under harsh climatic conditions. It consists of a total 68 turbines. The first phase of the project consists of 20 Siemens SWT-2.0-76 with a total capacity of 40 MW with a construction period over October 2002 to September 2002 and an annual production of 120 GW.hr. The second phase consists of 48 Siemens SWT-2.3-82 turbines with an installed capacity of 110.4 MW, with a construction period from December 2003 to December 2005 and an annual production of 330 GW.hr.

**DHULE, INDIA WIND PARK**

Figure 15. Dhule, India wind-park uses the Suzlon S64-1.25 MW wind turbines. The stripes painted on the rotor blades are intended as a visual warning to flying birds.

The Dhule wind park site, located approximately 30 km from the town of Nandurbar in Maharashtra, India, is spread across a vast, undulating expanse.

The site experiences good wind conditions around the year, with an average air density of 1.078 $kg/m^3$ and a mean annual wind power flux (density) of 289 $kW/m^2$, extrapolated at a height of 30 meters.

The site has 400 MW of installed capacity featuring mainly the Suzlon S64-1.25 MWe model, and plans to add a further 600 MW capacity. At a planned 1,000 MW capacity, the Dhule wind park is poised to become among the world's largest wind parks.

## EXERCISE

1. Assuming the same pressure drop and density, estimate the percent increase in wind speed due to the tunnel effect for a decrease of the constriction or contraction ratio from $\beta = 0.9$ to $\beta = 0.5$.

## REFERENCE

1. Kevin Bullis, "Better Computer Models Needed for Mega Wind Farms," Technology Review, April 17, 2013.