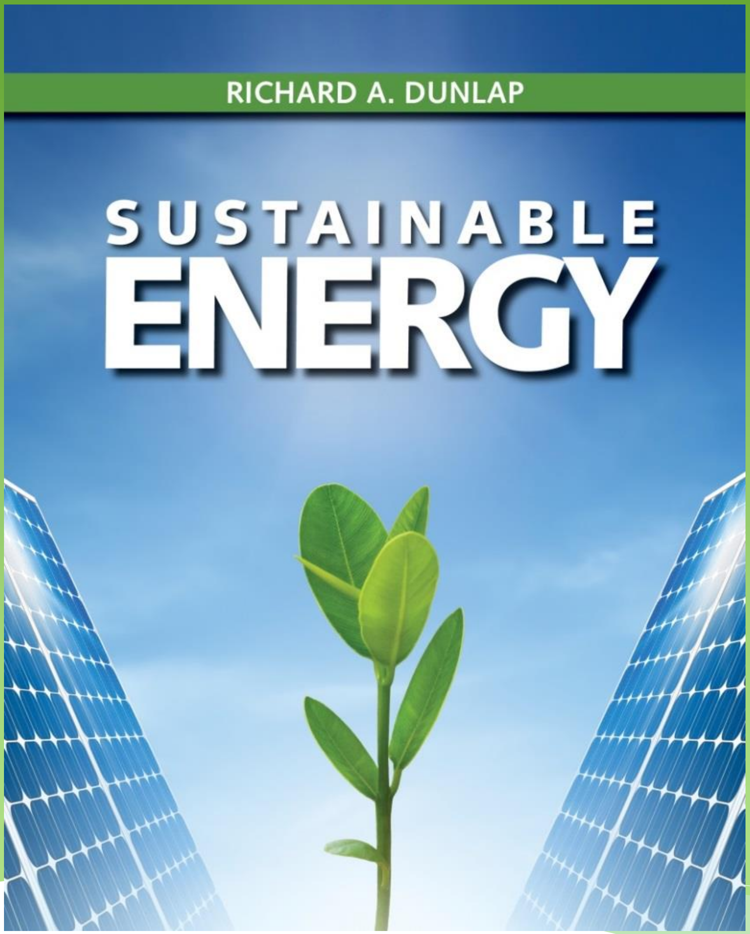
Sustainable Energy



Chapter 10

* Wind Energy

CENGAGE Learning

Learning Objectives

- The different designs of wind turbines.
- The physics of the energy content of wind.
- The efficiency of different wind turbine designs and the importance of the tip speed ratio.
- The geographic distribution of wind energy.
- The design of wind farms.
- The utilization of wind energy worldwide.
- Advantages of offshore wind farms.

For centuries wind energy has been used for transportation

Figure 10.1: The *Royal Clipper*, the largest operational sailing ship as of 2014.

Wind energy used for grinding grain (left) and pumping water (right)

Figure 10.2: Traditional four-blade Dutch windmill in the Netherlands.

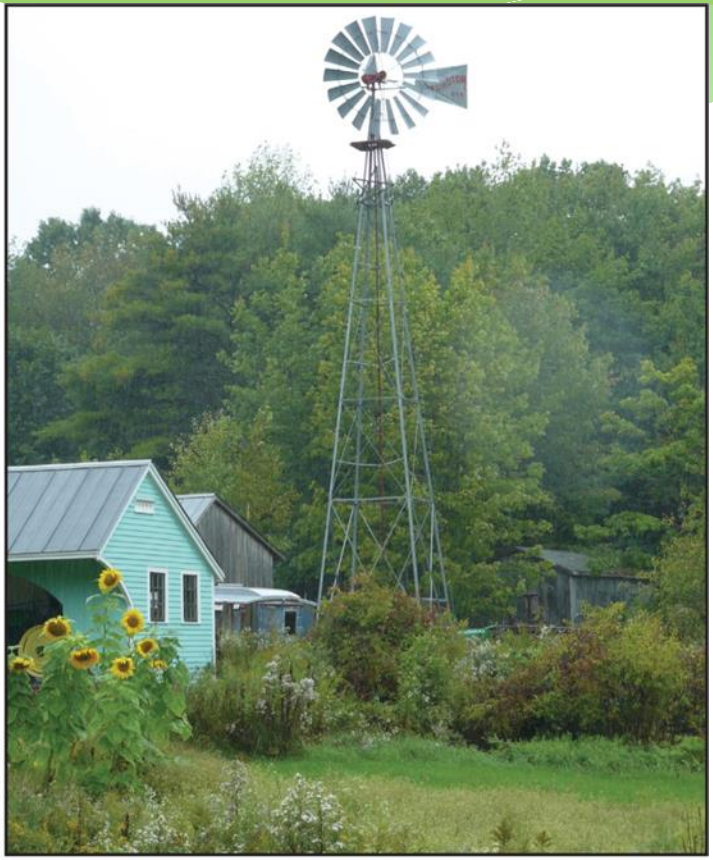


Figure 10.4: American multiblade windmill in Maine.

Modern wind turbines

horizontal axis turbines (left) and vertical axis turbines (right)

Figure 10.6: Modern three-blade wind turbine at Digby Neck Wind Farm, Nova Scotia. Turbine is a 1.5-MW GE 1.5sle with a rotor diameter of 77 m and a hub height of 80 m.

Figure 10.5: Darrieus rotor on Îles de la Madeleine, Québec.

Nacelle of a horizontal axis wind turbine

Figure 10.8: Nacelle of a 600-kW wind turbine.

Calculation of Wind energy

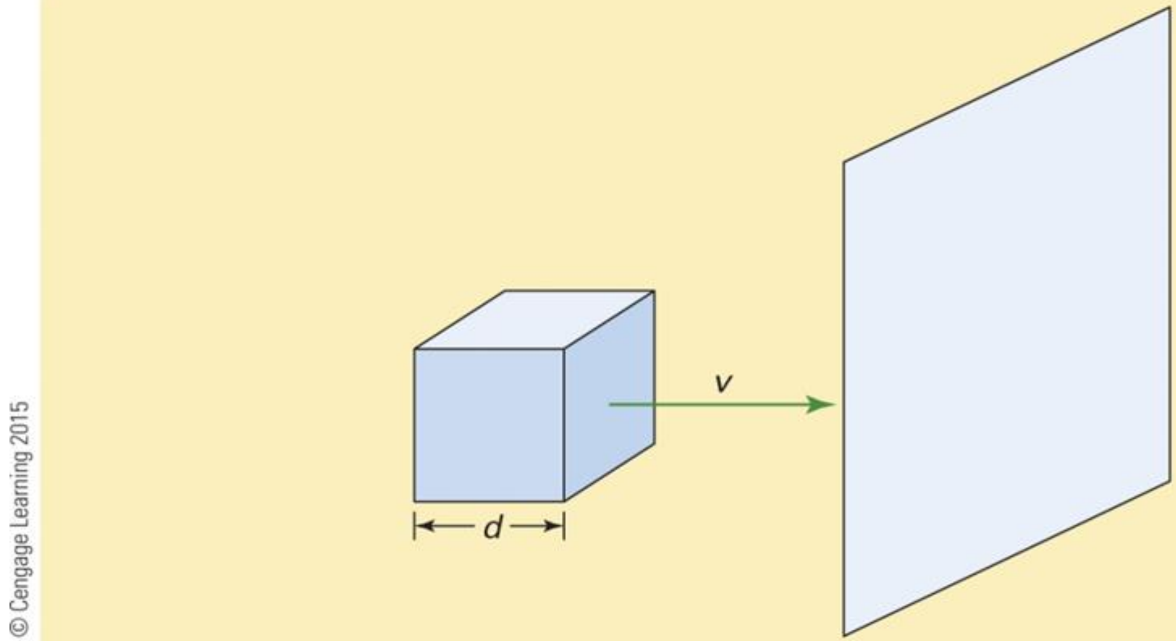


Figure 10.10: Cubic parcel of air with dimensions $d \times d \times d$ traveling with velocity v and passing through a plane parallel to one of its faces.

Wind energy and power

The kinetic energy associated with this mass of air is

$$E = \frac{1}{2} mv^2 = \frac{1}{2} d^3 \rho v^2 \qquad (10.1)$$

The time required for the parcel of air to pass through the plane is t=d/v and the corresponding power is

$$P = \frac{E}{t} = \frac{1}{2} d^2 \rho v^3 \qquad (10.2)$$

Wind power per unit area

The power per unit area is

$$\frac{P}{A} = \frac{P}{d^2} = \tfrac{1}{2}\rho v^3 \qquad (10.3)$$

Using the density of air $\rho = 1.204\ \mathrm{kg/m^3}$ gives

$$\frac{P}{A} = (0.602\ \mathrm{kg/m^3})v^3 \qquad (10.4)$$

Rotor efficiency

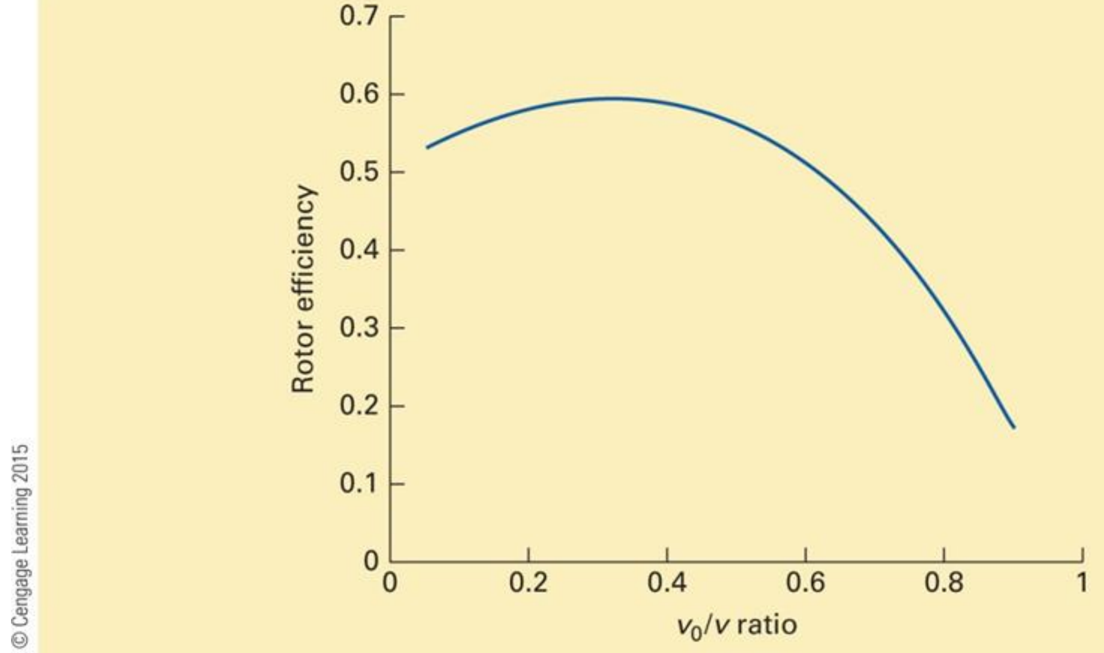


Figure 10.11: Wind turbine efficiency as a function of the relative air velocity after passing through the wind turbine.

The efficiency of different turbine designs as a function of tip speed ratio

Based on E. Hau, Wind Turbines: Fundamentals, Technologies, Application Economics, 2nd ed., Springer 2006

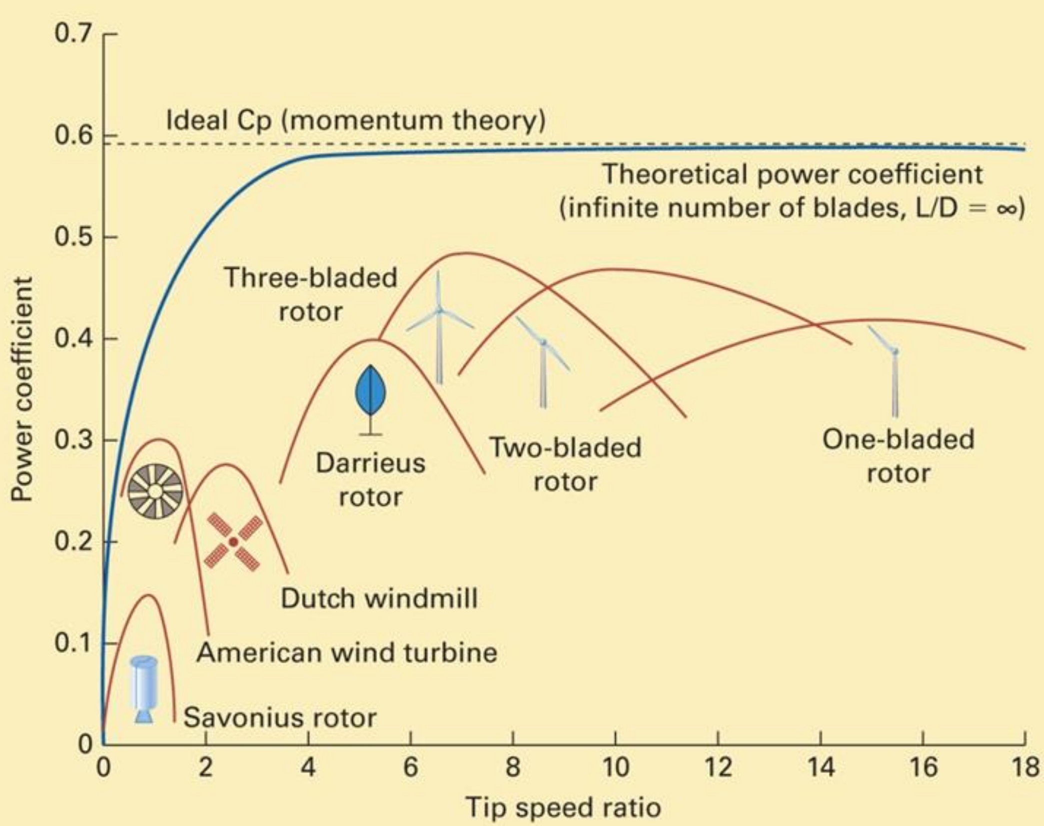


Figure 10.12: Efficiency as a function of tip speed ratio for different wind turbine designs.

Cut-in and cut-out speeds

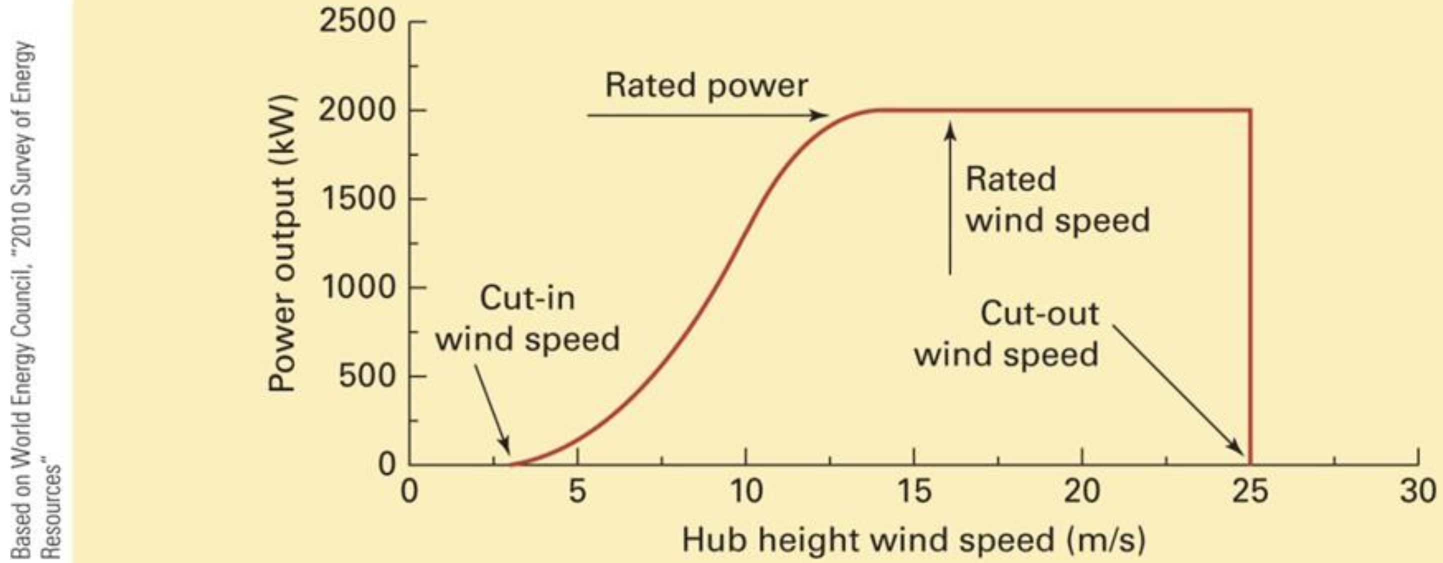


Figure 10.13: Power output for a 2-MW wind turbine as a function of wind speed.

Effects of ground friction and altitude

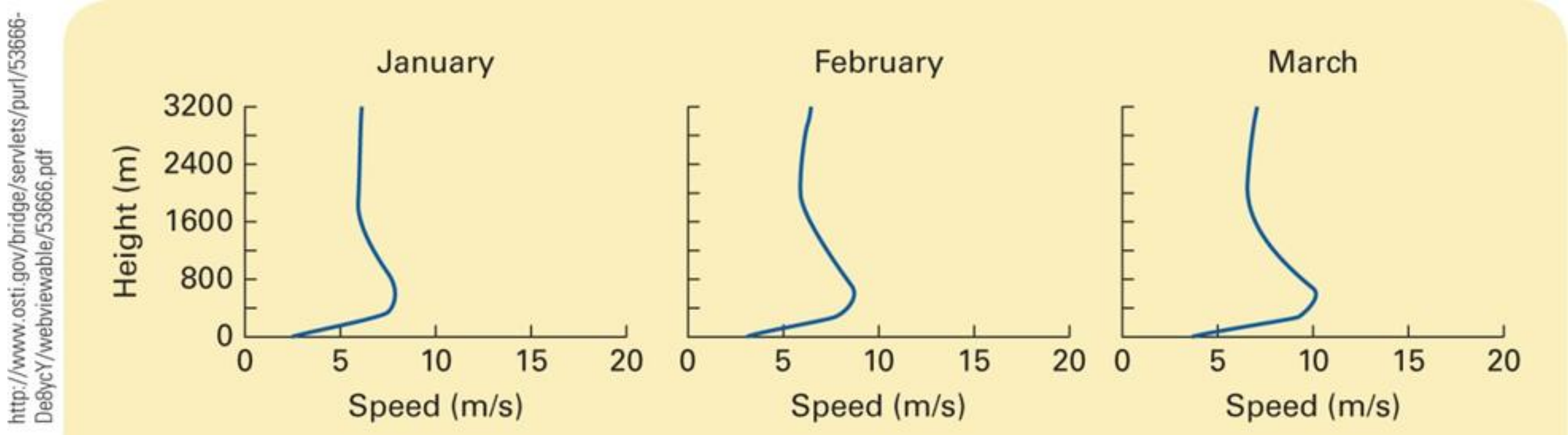
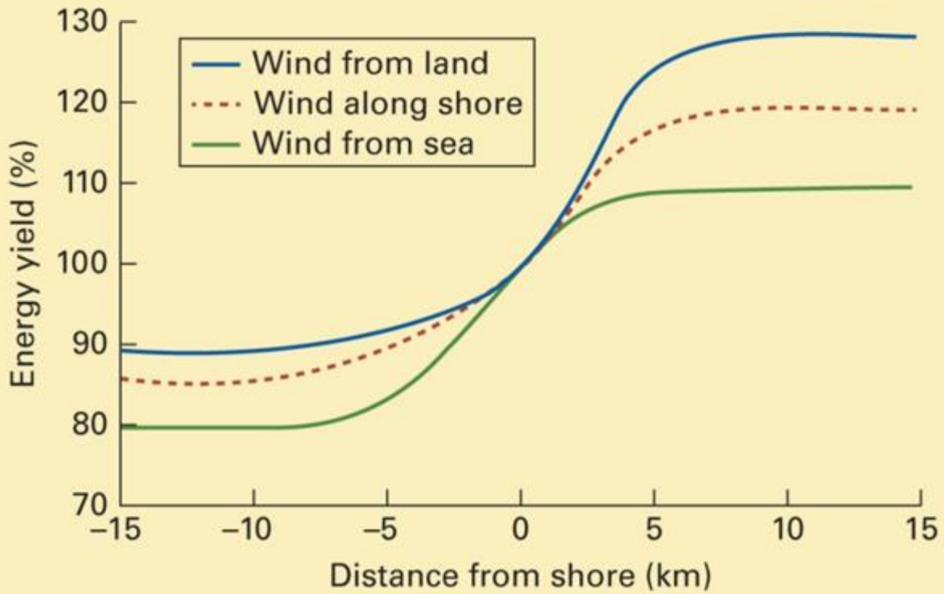


Figure 10.16: Typical variation of wind speed with altitude.

Near the coast, wind speed increases offshore



Based on M. R. Patel, Wind and Solar Power Systems, Design, Analysis, and Operation. CRC Press, 2006

Figure 10.17: Variation of wind energy near seacoast.

Wind turbine location

These factors indicate the importance of the design of the wind turbine tower and the location of the turbine.

Multiple turbines can be combined into wind farms.

Wind farms require optimal spacing of turbines to maximize power produced per unit land area

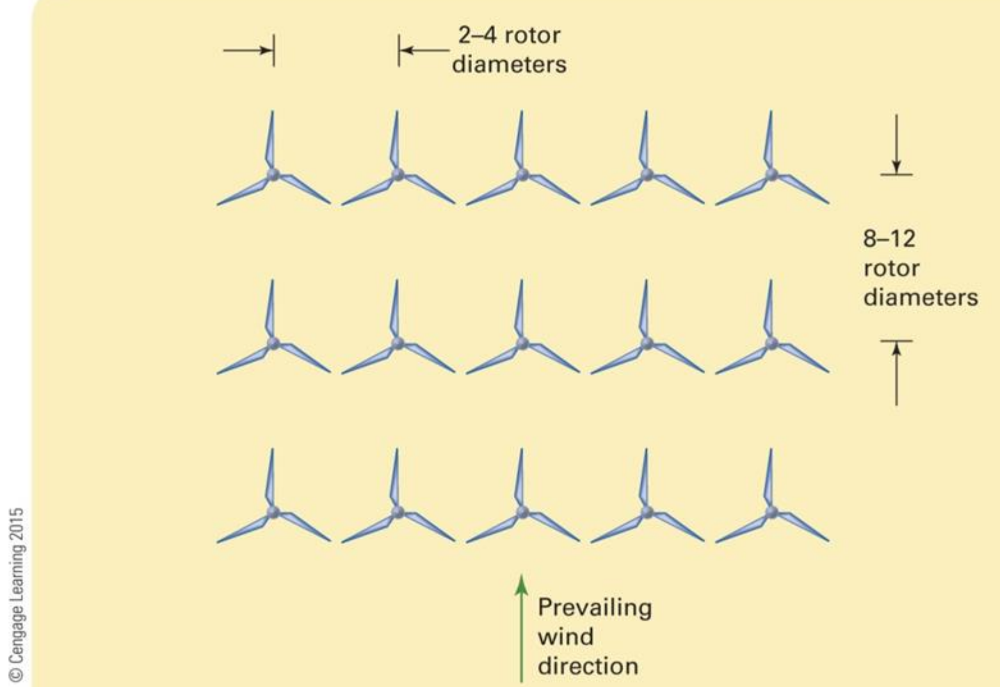


Figure 10.18: Optimal spacing of wind turbines in a wind farm. Distances are shown as a function of the rotor diameter.

Applications of Wind Power

In the United States the most viable wind resources are along the Atlantic and Pacific Coasts and in the Great Plains.

Wind power in the United States

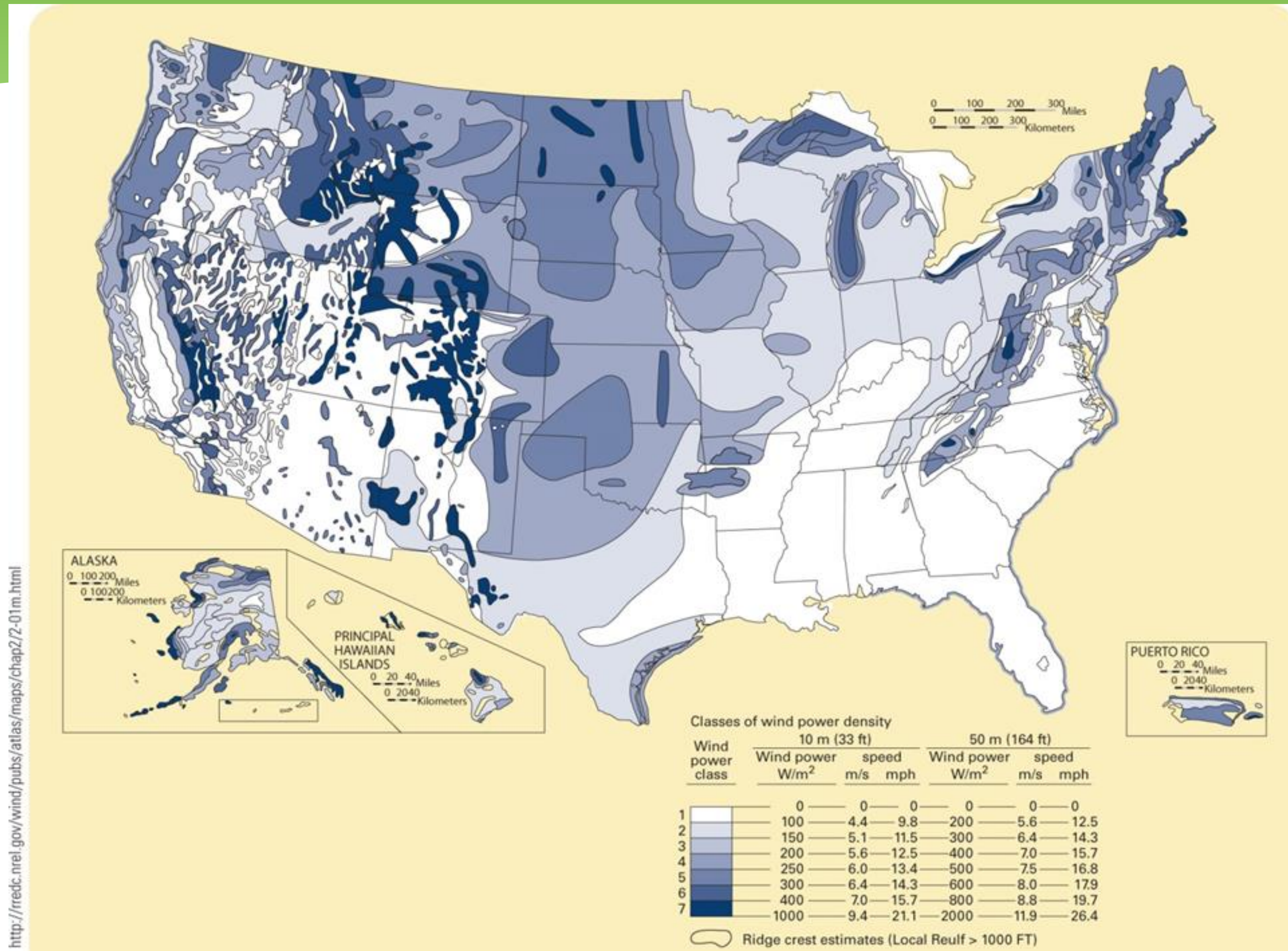


Figure 10.19: Average wind power (in W/m²) for the United States.

Examples of wind turbine applications on different scales

small residential wind turbine

Figure 10.20: Small residential wind turbine.

Medium size grid connected wind turbine

Figure 10.21: 600-kW wind turbine in Goodwood, Nova Scotia.

Wind farm

grid connected wind farm

Figure 10.22: Tehachapi wind farm in California.

Grid connection must ensure that frequency and voltage are matched to grid characteristics

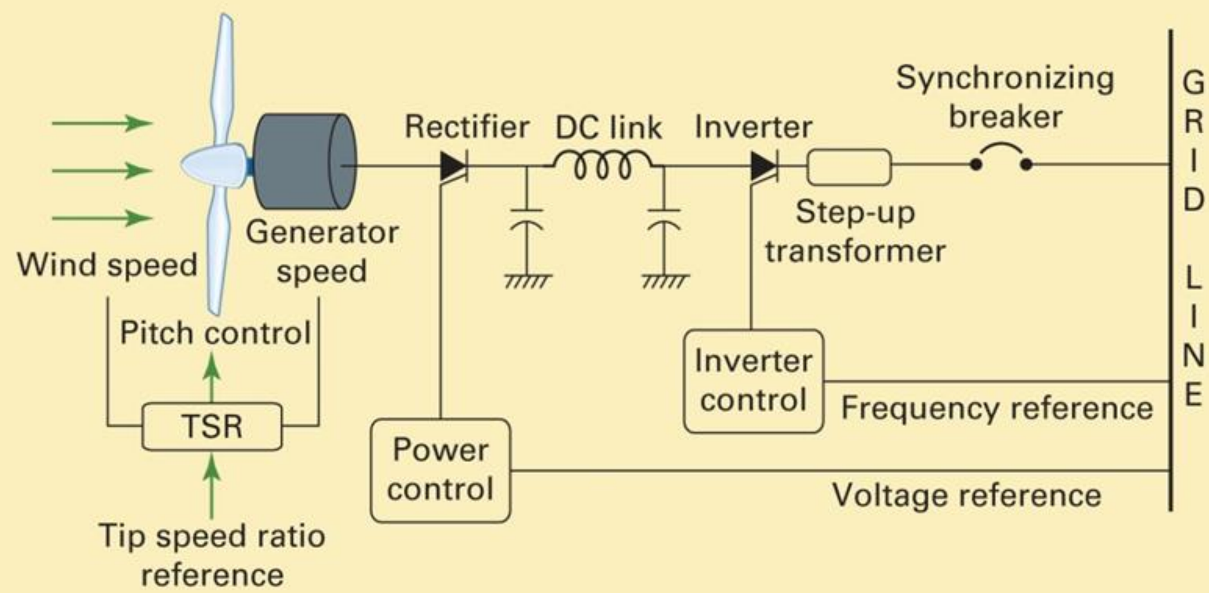


Figure 10.23: Schematic of grid-connected wind turbine system.

Based on M.R. Patel, Wind and Solar Power Systems: Design, Analysis, and Operation (2nd ed.), CRC Press 2006

Installed wind capacity for some countries (2007)

Table 10.1: Installed wind power as of 2007.

country	installed capacity (MW_e)	capacity per capita (W_e)
Germany	22,247	270.6
United States	16,818	55.0
Spain	15,145	328.5
India	8000	7.0
China	6050	4.6
Denmark	3129	568.9
Italy	2726	45.7
France	2454	38.1
United Kingdom	2389	39.0
Portugal	2150	202.8
Canada	1856	55.6
Netherlands	1747	105.9
Japan	1538	12.0
Austria	982	118.3
Greece	871	77.8
Australia	824	38.3
Ireland	805	182.9
Sweden	788	85.7

Nations with the most active wind power development

Germany, the United States and Spain have the greatest installed wind capacity.

On a per capita basis Denmark, Spain and Germany are the most active in this area.

Much of Denmark's wind capacity is from offshore wind farms

Tony Moran/Shutterstock.com

Figure 10.24: Danish offshore wind farm.

Environmental consequences of wind power

Wind power has some (although fairly minimal) environmental effects.

A description of some of the potential disadvantages of wind power follows:

Noise

1. Noise - this is a local concern for residents living within a kilometer or so of the wind turbine.

Effect on wildlife

2. Effect on wildlife (i.e. risk to birds, bats, etc.) - studies have shown that other anthropogenic factors (power lines) vehicles, plate glass windows, etc.) are a greater concern.

Effect on land use

3. Effect on land use - wind power is more compatible with dual land use than many other forms of energy. In many cases wind power and agriculture or solar energy can utilize common land. The low power density of wind means that substantial land area would be needed to replace current energy sources such as fossil fuels and nuclear.

Aesthetics

4. Aesthetics - a concern associated with virtually all energy production methods.

Accidents

5. As well, accidents can result from turbine failure
e.g. generator fires, tower collapse or blade breakage (or a combination of these).

These are a concern for nearby residents and roadways.

Summary

- The kinetic energy associated with moving air is related to the cube of its velocity
- Wind turbines extract energy from moving air and convert it into electrical energy
- Different wind turbine geometries have different efficiencies
- Available wind energy depends on location
- Generally available wind energy increases with altitude and distance offshore
- Wind farms combine numerous turbines which can be placed to optimize power production
- Development of wind power is being actively pursued by a number of different countries
- Denmark, Spain and Germany have the greatest installed wind capacity per capita