Earth. In summer, winds loaded with moist air blow onshore and cause heavy rains; in winter, dry continental air blows offshore. This pattern is strong in India and West Africa.

Other local patterns are found associated with the land and ocean interface. An example is the sea–land breeze, which changes daily; it blows from sea to land at daytime, and from land to sea at nighttime. This reversal is due to the differential heating of land and sea.

13.2 WIND POWER

13.2.1 Power in the Wind

Recall from Chapter 1 that for a fluid flowing with velocity v, the power is $p(t) = \frac{1}{2}\dot{m}v^2$, where $\dot{m}$ is the fluid mass flow rate, and $\dot{m} = \rho A v$ assuming a simple geometry of cross-sectional area A, normal to the direction of flow. With these elements, we find that power W available is proportional to the cube of velocity of the fluid

$$p(t) = \frac{1}{2}\rho A v^3 \tag{13.1}$$

We have used this equation in Chapter 12 for calculations of power in the flow of water. Now, in dealing with air, we use air density. The density of air changes according to elevation above sea level and temperature. To specify wind turbine performance, there are *reference conditions*, which are pressure 1 atm, temperature 15°C, and density 1.225 kg/m3.

A depends upon the rotor diameter, which depends upon the turbine design. When we divide Equation 13.1 by A, we obtain *specific power* or *power density* in W/m^2

$$p(t) = \frac{1}{2}\rho v^3 \tag{13.2}$$

which is simply *power per unit of cross-sectional area*. Since area goes with the square of diameter, doubling the rotor diameter quadruples the available power. This helps explain why use larger wind turbines: they are more economical because the turbine cost is just proportional to rotor diameter, whereas the power generated is proportional to the square of the diameter [2].

Example 13.2

The simplest calculation would be to assume density to be known and unit area. What would be the specific power or power density for wind velocity of ~~1~~ 10 m/s at reference conditions? Answer: $p(t) = \frac{1}{2}\rho v^3 = \frac{1}{2}1.225 \times 10^3 = 612.5$ W/m2.

Function pow.rho.v3.table of renpow performs this calculation:

```
> x <- list(rho=1.225,v=10,A=1)
> pow.rho.v3.table(x)
$X
 Density(kg/m3) Vel(m/s) Area(m2) Power(W)
1         1.225   10       1   612.5
```

To visualize the effect of density and wind speed, we can use functions pow.rho.v3 and pow.v3.plot for a range of density and wind

```
x <- list(rho=c(0.9,1,1.1,1.225,1.3),v=seq(0,30),A=1)
X <- pow.rho.v3(x)
x <- list(v=X$v,y=X$rho,Pow=X$Pow,yleg="rho",ylabel="Density(kg/m3)")
pow.v3.plot(x)
```

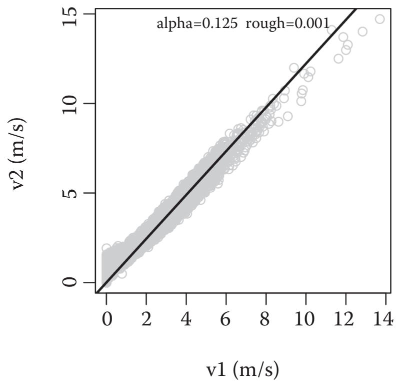

FIGURE 13.13 Calibration of wind speed versus height function from data collected at two different heights.

Example 13.8

Consider data on wind speed for two anemometers on the same tower. The area is relatively open with grass cover and several small buildings nearby. The lowest gauge is at 2 m above the ground, and the other at 10 m above the ground. The data consists of wind speed averaged every 15 min for 3 months from mid May to mid August 2017.

```
Read the data file by using
# reading file
tt.xx<-read.table("extdata/TEODP2017.csv", header=TRUE, sep=",", skip=1)
```

Alternatively, we can use the system file

```
tt.xx  <-  read.table(system.file("extdata","TEODP2017.csv",  package="renpow"),
header=TRUE, sep=",", skip=1)
```

```
Alternatively load it from renpow data.  This should be regular font not script font.
tt.xx <-TEODP2017

Select the average wind speed at two heights which are variables 8 and 4.
ws.2m.10m <- tt.xx[,c(1,8,4)]
v1.v2<- ws.2m.10m[,2:3]
> x <- list(v1.v2=v1.v2,H1=2,H2=10)
> cal.vH(x)
$alpha
[1] 0.125
$rough
[1] 0.001
>
```

The function produces the plot shown in Figure 13.13. We have $\alpha = 0.125$ and $l = 0.001$. These are reasonable values for open grassy areas. Note from Figure 13.13 that the zero-intercept regression is better once the lower level wind speed is above 2 m/s. In fact for low wind speed, you would see slow speed at the top anemometer when the lower anemometer is not even moving.

13.3 STATISTICS OF WIND SPEED

In the same manner as other forms of renewable power, the wind resource varies randomly and we must understand this variability to estimate how much power we may harvest during a particular week, month, or season. Very importantly, average wind speed for a location does not alone indicate the energy a wind turbine could produce; frequency of wind speeds at various intervals is also

A good fit to wind speed is often found for $k = 2$, or a Rayleigh distribution as given in Equation 13.19. The mean or expected value of a Rayleigh pdf is related directly to the scale c [2].

$$\mu_v = E(v) = \int_0^{\infty} v p(v) dv = \frac{\sqrt{\pi}}{2} c \tag{13.20}$$

A first step to find a fit to Rayleigh is to assume shape $k = 2$, use Equation 13.20 to determine the scale from the mean wind speed, and estimate the mean of wind speed by its average

$$c = \frac{2\mu_v}{\sqrt{\pi}} \simeq \frac{2\bar{v}}{\sqrt{\pi}} \tag{13.21}$$

where $\bar{v}$ is the sample mean or arithmetic average of all values. Once we have a model, we can calculate the probability of having a range of given wind speed.

Example 13.9

Estimate the parameters of a Rayleigh distribution for a location with average wind of 2.5 m/s. Plot the pdf and cdf using weibull.plot. Determine the probability that wind speed is above 2 m/s and above 3 m/s. Answer: The shape is $k = 2$, then use $c = \frac{2\bar{v}}{\sqrt{\pi}} = \frac{2 \times \cancel{5}\ 2.5}{1.77} = \cancel{5.65}\ 2.82$. To find the probability that wind speed is above 2 m/s, we use the pweibull function:

```
> weibull.plot(xmax=10,scale=2*2.5/sqrt(pi),shape=2)
> 1 - pweibull(c(2,3),scale=2*2.5/sqrt(pi),shape=2)
[1] 0.6049226 0.3227190
> abline(v=2,lty=2);abline(v=3,lty=2)
>
```

The plot is shown in Figure 13.15, including the two vertical lines for v = 2 and v = 3 on the cdf to emphasize the points at which we seek the probability. These are $Pr[v > 2] = 1 - Pr[v \leq 2] = 0.605$ and $Pr[v > 3] = 1 - Pr[v \leq 3] = 0.323$. Concluding that the wind will exceed 2 m/s 60% of the time and 3 m/s 32.3% of the time.

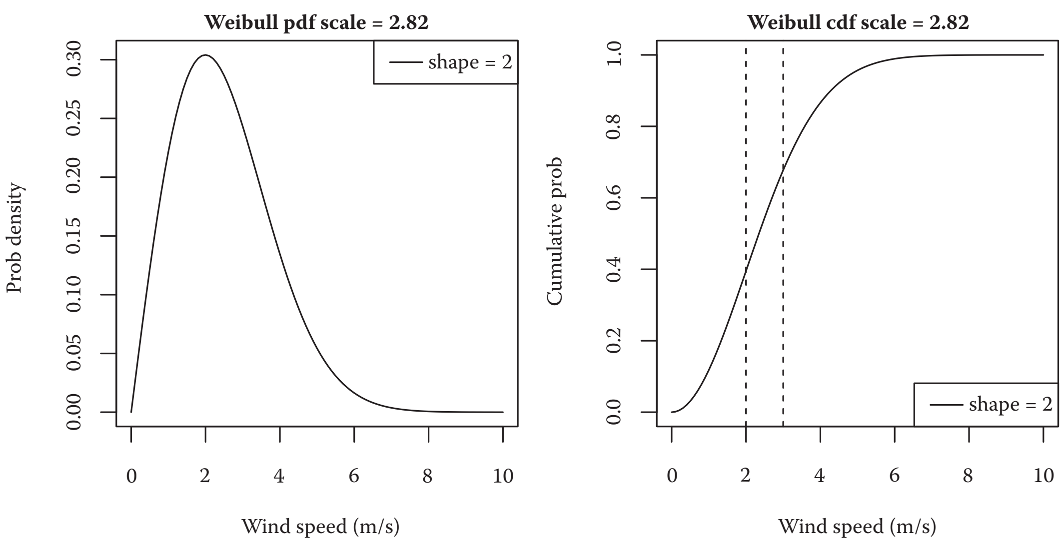

FIGURE 13.15 Example of Rayleigh distribution.

losses, as the wind is affected by the blades. This was not accounted for in the Betz limit, since it assumes the wind does not change direction as it goes through the rotor. As mentioned earlier, after taking into account all of these other losses, modern wind turbines have an efficiency of 45% to 50%.

13.4.4 Wind Turbine Generators

Recall from our discussion of generators in previous chapters (8, 10, and 11) that the frequency is fixed to that of the grid. We have dealt with synchronous generators, such that the rotational speed is fixed to match the electrical frequency of the grid. That is how most electricity is generated in the world from coal-fired power plants, natural gas-fired plants, nuclear, and hydroelectric. Denote by N_s the synchronous speed, in rpm by f the frequency, and p the number of poles we have

$$Ns = \frac{60\frac{\text{sec}}{\text{min}} \times f}{p/2} = \frac{120 \times f}{p}$$

$$N_s = \frac{120 \times f}{p} \tag{13.40}$$

For instance, for 60 Hz and 6 poles, the rotation frequency is $N_s = \frac{120 \times 60}{\cancel{4}\ 6} = \cancel{1800}\ 1200$ rpm.

However, wind power generation uses *asynchronous generators*, meaning that they are not rotating at a fixed speed. Most wind turbines use *induction generators*, which at low speeds behave as a motor and at higher speeds as a generator. A common induction motor employed in wind turbines is a *squirrel cage generator* (SCIG), so named because the rotor of the generator resembles a cage made out of rings and bars; the bars are shorted at the rings (Figure 13.22). The magnetic field is created by the stator, not the rotor, which is fed with three-phase alternating current (AC). An advantage of this design is that there is no need for brushes and slip rings to connect to the rotor.

When the high-speed shaft of the wind turbine rotates the generator rotor, it starts turning at a slower speed N_r than N_s, and behaves as a motor. However, once the machine is turning faster than the synchronous speed, it behaves as a generator and feeds three-phase power back to the stator windings. The slip s is defined as a relative difference between the two rotation frequencies

$$s = \frac{Ns - Nr}{Ns} = 1 - \frac{Nr}{Ns} \tag{13.41}$$

For instance, take 60 Hz and $p = 4$. We know $N_s = 1800$ rpm from Equation 13.40. For grid-tie, we want the slip to be low, say ±1%. When $s = 1\%$, then N_r is $Nr = (1 - s)Ns = 0.99 \times 1800 = 1782$ rpm, and the machine behaves as a motor. However, for negative slip $s = -0.01$ or -1%, the rotational frequency $Nr = (1 - s)Ns = (1 - (-0.01)) \times 1800 = 1.01 \times 1800 = 1818$ rpm behaves as a generator.

Since the generator is driven by the high-speed shaft, its gear ratio affects the turbine rotor speed. Suppose the gear ratio was G:1; then the turbine will have to rotate at $1800/G$ rpm. At this point, you need to link this concept to the one that relates turbine efficiency to rotational speed as a function of wind speed. You can see that matching requirements of turbine speed for efficiency to the generator

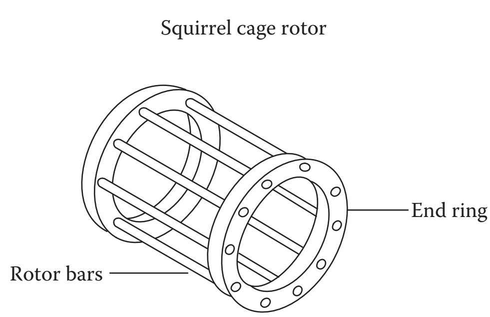

FIGURE 13.22 Squirrel-cage rotor of an induction generator.

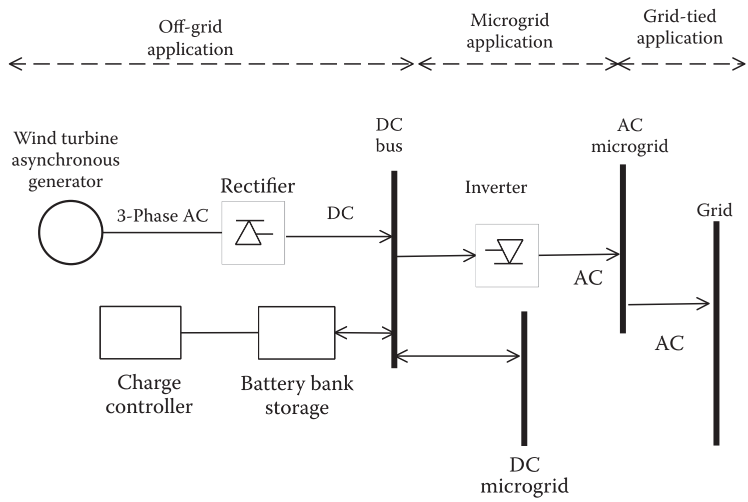

FIGURE 13.25 Small wind turbine and asynchronous generator used for off-grid or microgrid applications and optional connection to the grid.

The DC bus voltage for a small system is typically 12, 24, or 48 V. Higher voltage is advantageous because it reduces current, while maintaining the same power. Lower current reduces wire ohmic losses and allows for smaller wires, breakers, and fuses. This makes it simpler and reduces costs. For instance, for 1.2–2.4 kW systems, using 24 V would keep current below 100 A, but a 2.4–4.8 kW system would require 48 V to keep the current below 100 A.

The wind turbine has specifications (cut-in, rated, and cut-out wind speed), a power curve, and efficiencies as we previously discussed. The rectifier, charge controller, and inverter have their own efficiencies. For instance, typical values are 80%–90% for the inverter and 95%–98% for the charge controller.

Example 13.21

Suppose we have an off-grid system composed of a small 1 kW wind turbine of rotor area 4 m^2 and 0.4 efficiency with cut-in ~~2~~ 2.5 m/s, rated 10 m/s, and cut-out 30 m/s. The winds are Rayleigh with average of ~~5~~ 6 m/s. The daily AC load energy demand is 3 kWh with peak power demand of 1.5 kW. The inverter efficiency is 85% and the charge controller efficiency is 97%. We will not consider the batteries in this example. Determine suitable voltage, the peak current, DC load, and CF. Does the expected energy from the turbine cover the demand? Answer: The DC load is

$$E_{DC} = \frac{E_{AC}}{\eta_{inv} \times \eta_{cc}} = \frac{3\text{kWh/d}}{0.85 \times 0.97} \simeq 3.64 \text{ kWh/d} \tag{13.47}$$

For a peak load of 1.5 kW we could use 24 V, which will keep current below its peak of $I_{peak} = \frac{1500}{24} = 62.5$ A. Now, use the functions of renpow with specs and winds above

```
x <- list(cutin=2.5,vrated=10,cutout=30, A=4,v=seq(0,35,0.1))
Pow <- power.curve(x)
> wind.energy(x,Pow,avg=6)
$energy
[1] 2675.07
```

Perceived public concerns with wind turbines include noise. Noise from wind turbines is mainly from the rotating blades and this increases with wind speed. However, for large turbines, relative noise level has been reported to be about 40 dB(A) at 300 m away from a turbine. Just for comparison, this is about the same level as experienced in a typical home or office. For small turbines, noise can be higher closer to the turbine and at higher wind speeds, but decreases with the number of blades.

A major environmental concern has been the impact on wildlife, particularly interference with avian and bat species habitats. Elevated counts of bird strikes have been reported at some locations but has not been a reported problem in many other locations. This indicates that when evaluating sites for wind farms or offshore facilities, accounting for avian habitat and migration routes could help reduce these negative impacts. Less research has been conducted on the impact of small wind power generating stations on avian populations and bats.

EXERCISES

13.1. What type of rotation (clockwise or counterclockwise) would you expect for typhoons in the Northwest Pacific and for cyclones in the South Pacific?

13.2. What would be the specific power or power density for wind velocity of 3 m/s at reference conditions? What would be the air density at 2000 m asl and 5°C?

13.3. Plot specific power for four elevations—0, 200, 500, 1000 m asl—and wind speed from 0 to 30 m/s. Use ground temperature of 25°C and lapse rate of 6°C/km.

13.4. Compare wind speed ratios $\frac{v}{v_0}$ and power ratio $\frac{P}{P_0}$ obtained from the empirical exponential model with the aerodynamics model for $\alpha = 0.25$ and $l = 0.4$.

13.5. Estimate the parameters of a Rayleigh distribution for a location with average wind of 3.5 m/s. Plot the pdf and cdf. Determine the probability that the wind speed is above 3 m/s and below 5 m/s.

13.6. Suppose we have Rayleigh winds with $\bar{v} = 3.12$ m/s and $c = 3.52$. What is the estimated average power in the wind at standard conditions?

13.7. How much power per m^2 would you ideally extract from a wind turbine at standard conditions of density 1.225 kg/m^3 and 15°C when the wind speed at 10 m is 5 m/s and the turbine is on a tower 20 m above the ground? What is the downwind wind speed? Assume the terrain is ~~shrub and small trees~~. rural with α=0.2.

13.8. What is the optimum angular frequency for a three-blade rotor of 15 m radius in 5 m/s wind? What is the TSR for this angular speed? What is the gear ratio required to match the rpm of a 4-pole generator producing 60 Hz?

13.9. Assume cut-in, rated, and cut-out wind speeds are 3, 10, and 30 m/s, respectively. We have Rayleigh winds with 5 m/s average. Calculate number of hours with expected generation at rated power, expected generation, and CF.

13.10. Consider an off-grid wind power system with a DC load 4 kWh/d and peak DC load of 1.5 kW. The cut-in, rated, and cut-out wind speeds are 3, 10, and 30 m/s, respectively. We have Rayleigh winds with 5 m/s average. Design a battery bank that would provide enough power for 2 days of wind of speed below cut-in with a DOD not to exceed 70%. Assume batteries are kept at room temperature.