Chapter 9

Wind

"First, there is the power of the Wind, constantly
exerted over the globe…
Here is an almost incalculable power at our disposal,
yet how trifling the use we make of it!
It only serves to turn a few mills,
blow a few vessels across the ocean,
and a few trivial ends besides.
What a poor compliment do we pay to our
indefatigable and energetic servant!"

Henry Thoreau, 1817–1862.

The global installed capacity of wind is expected to continue its rapid growth. Over the five years up to 2022, the cost of wind projects is predicted to drop by 14% as the industry continues along the learning or experience curve (Lienhard *et al.*, 2016). It should be noted that wind power technology needed quite a long time before it took off commercially to become a significant part of total power generation. More than 93% of the investments in onshore wind from 1983 to 2014 occurred after the year 2000. As shown in Figure 3.6, the installed wind power capacity is negligible in African countries compared to

doi: 10.2166/9781780409443_0111

China, India, North America and Europe. Unquestionably there is a huge wind power capacity waiting to be utilised.

The fundamental properties of a wind turbine power are explained in 9.1. Like solar PV, the wind turbine produces power intermittently. Therefore, the wind capacity factor is important to know, as explained in 9.2. Intermittent production and the need for energy storage is the topic of Chapter 10, while economic and financing aspects for renewable energy are described in Chapter 12.

9.1 BASIC PROPERTIES OF WIND TURBINE POWER

The kinetic energy from the wind creates the rotational energy of the wind turbine. Then a generator converts the rotational energy into electric energy.

Obviously, the generated power of wind turbines depends on the wind speed. Theoretically, it is proportional to the cube of the wind speed. This means than when the wind speed is doubled, the wind power increases by a factor of eight. If the wind speed is too low, then the turbine does not produce any power and it may also stop producing power if the wind speed is too high. It is also a well-known fact that the wind speed can change within minutes, so the generated power from a single turbine is apparently quite variable. If several turbines are combined in a wind farm, then the variability can be reduced. Today it is common that turbines generate electric power at varying speeds, so the rotor is continuously matched to the wind speed. This will of course utilise the wind power more than if the turbine generated electric power only at a given rated speed.

When the wind speed doubles the wind power increases eight times.

The kinetic energy stored in a flow per unit volume is

$$E = \frac{1}{2} \cdot \rho \cdot v^2$$

where ρ is the density of the air. For a stream flowing through a transversal area S (here it is the area that is swept by the wind turbine) the flow rate is $S \cdot v$. The generated mechanical power P is determined by both the wind speed and the area S according to the so-called Betz formula:

$$P = \frac{1}{2} \cdot \rho \cdot S \cdot v^3$$

where ρ is the density of the air. The available energy in the wind is obtained by integrating the power during a time interval T_p, typically one year:

$$E_{\text{annual}} = \frac{1}{2} \cdot \rho \cdot S \int_0^{T_p} v^3 dt$$

The Betz formula explains clearly that the wind turbine power increases significantly not only with the circular area S but also with the tower height. At higher levels the wind is less disturbed by surrounding objects like hills and buildings. Also, wind speeds in the lower atmosphere increase with elevation and this is important given the v^3 dependence of extracted energy.

A wind generator requires a minimum wind velocity of 3–5 *m/s* and will deliver the nominal capacity at a wind velocity of 12–14 *m/s*. Wind turbines have been developed to have a favourable operating condition at 10–12 *m/s*. These wind towers have a larger rotor diameter per *kW* of power. At high speeds small-scale generators, for safety reasons, are blocked by a braking system. High-power wind generators turn the rotor blades to stop the rotation and the mechanical brakes are used only for gross failures. There are generators that can adjust to the wind direction so that the power output is constant.

The wind generator speed is variable since the wind speed is not constant. The AC power frequency delivered, however, should be constant. Therefore, the rotors of the generator are connected to inverters to control the voltage and frequency of the AC power delivered.

Globally wind power has been developing towards larger wind turbines and higher power outputs. The largest commercial turbines today (Vestas) have a power rating exceeding 9 *MW*. For our purposes of decentralised power sources outside the grid we will consider much smaller systems.

Not surprisingly, small wind power units have a higher capital cost per *kW* compared to large systems. For the considered off-grid applications we will focus on small wind turbines (SWT). There is a wide range of small-scale turbines, from 'micro SWTs' rated at less than 1 *kW* to 'midi SWTs' reaching 100 *kW*. They are commonly used as stand-alone electricity systems in off-grid locations. Obviously, if the location is not windy there is a lower load factor and a higher capital cost per *kW*. Another challenge is wind turbulence caused by obstacles in the surroundings. A high tower will reduce this turbulence but will increase the cost. Simply put, a turbine with a larger tower and a relatively larger rotor (compared to its maximum power output) will produce more energy per installed unit of capacity. The wind velocity on hills and ridges can be higher. On the other hand, the air density is lower at high altitudes. In cold climates the air is denser in winter, resulting in more wind energy.

A problematic issue is that solar PV is an increasing competitor to wind power, as solar PV cost has dropped so dramatically during the last few years. For example, wind power water pumping can compete with solar power water pumping only at high wind speed and low solar irradiation value (Campana *et al.*, 2015). To find the most cost-effective solution for irrigation depends on the location. Another disadvantage of wind compared to solar PV is that the wind tower machinery needs frequent maintenance and repairs, which can be problematic considering the sub-Saharan conditions (Varadi *et al.*, 2018).

9.2 WIND POWER EFFICIENCY

Wind speeds can change significantly in just minutes. The output of wind turbines is therefore variable. As already noted, the output grows with rising wind speed and is constant above the rated wind speed.

Since the wind turbine cannot run at nominal speed continuously the real delivery of energy is expressed as the capacity factor. A wind turbine located offshore normally has a higher capacity factor than an onshore turbine. For example, onshore turbines in the UK have 26% while offshore wind has 35% (WEC, 2016, Chapter 10). In Denmark, a pioneering country in wind power, the power plants were running for 20–25% of the time in the 1980s and 1990s. In 2017 the offshore 160 *MWe* wind power park Horns Rev operated for some 3,500 hours or 40% of the time. The typical operating range for offshore is now 3,500–4,000 hours per year or 40–46%. Today large offshore wind power parks have a capacity of around 50% and will probably increase to 55–60% once 10 *MW* turbines have been installed (Svensson, 2018).

> The capacity factor for onshore wind power is of the order 25% while offshore can reach 50%.

It is apparent that the variability of wind power generation can be minimised if many wind turbines are connected in a large grid. When generation is connected over a large geographical area the local variations in wind can compensate for each other. As a result, the intermittency of wind generation can be reduced significantly. This means that off-grid wind turbines are more sensitive to changes in wind and local stand-alone wind turbines will have a relatively higher variability than a wind farm.

Wind energy technology is a mature technology and the systems operate at very high rates of availability. Availability of the turbine is the proportion of time the turbine is ready for operation. Onshore turbines typically have availabilities of 98%, while offshore turbine availabilities are slightly lower (95–98%). Today's turbines already extract nearly 50% of the energy conveyed in the wind.

Solar PV and wind can sometimes compensate for each other and create a less variable power production if they are connected. The wind may blow on a cloudy day or during the night, thus compensating for lack of solar power.

9.3 FURTHER READING

WEC (2016), Chapter 10 provides an easy-reading introduction to wind power. World Bank (2017) presents detailed information about global access to wind power.

IRENA (2015c) reports on technology quality for small wind turbines. A key issue is to limit the cost in developing markets but still maintain the reliability and quality of the systems.

For the interested reader the textbook by Manwell *et al.* (2011) gives an excellent introduction to wind power systems.