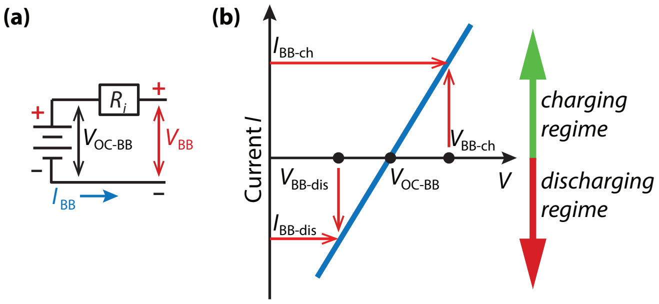

Figure 19.23: A simple model for (a) the equivalent circuit and (b) the I-V characteristics of a battery.

Note that we use the convention, where I_{BB} is positive when the battery is charged and negative when it is discharged. The resulting I-V characteristics of the battery bank is illustrated in Fig. 19.23 (b). In this figure, the charging regime and the discharging regime are depicted.

The current I_{BB} determines the power loss in the battery,

$$P_{\text{BB}}(\text{loss}) = I_{\text{BB}}^2 R_i. \tag{19.26}$$

This power always is lost, irrespective of the sign of I_{BB}, hence irrespective on whether the battery is charged or discharged.

19.3.3 Battery parameters

Let us now discuss some parameters that are used to characterise batteries.

Voltage

First, we will discuss the *voltage* rating of the battery. The voltage at that the battery is rated is the *nominal voltage* at which the battery is supposed to operate. The so called *solar batteries* or lead acid batteries for PV applications are usually rated at 12 V, 24 V or 48 V. The actual voltage of PV systems may differ from the nominal voltage. This is mainly depending on the SoC and the temperature of the battery.

Capacity

When talking about batteries, the term *capacity* refers to the amount of charge that the battery can deliver at the rated voltage. The capacity is directly proportional to the amount of electrode material in the battery. This explains why a small cell has a lower capacity than a large cell that is based on the same chemistry, even though the open circuit voltage across the cell will be the same for both the cells. Thus, the voltage of the cell is more chemistry based, while the capacity is more based on the quantity of the active materials used.

The capacity C_{bat} is measured in ampere-hours (Ah). Note that charge usually is measured in *coulomb* (C). As the electric current is defined as the rate of flow of electric charge, Ah is another unit of charge. Since 1 C = 1 As, 1 Ah = 3600 C. For batteries, Ah is the more convenient unit, because in the field of electricity the amount of energy usually is measured in watt-hours (Wh). The energy capacity of a battery is simply given by multiplying the rated battery voltage measured in volt by the battery capacity measured in Amp-hours,

$$E_{\text{bat}} = C_{\text{bat}} V, \tag{19.27}$$

which results in the battery energy capacity in watt-hours.

C-rate

A brand new battery with 10 Ah capacity theoretically can deliver 1 A current for 10 hours at room temperature. Of course, in practice this is seldom the case due to several factors. Therefore, the *C-rate* is used, which is a measure of the rate of discharge of the battery relative to its capacity. It is defined as the multiple of the current over the discharge current that the battery can sustain over one hour. For example, a C-rate of 1 for a 10 Ah battery corresponds to a discharge current of 10 A over 1 hour. A C-rate of 2 for the same battery would correspond to a discharge current of 20 A over half an hour. Similarly, a C-rate of 0.5 implies a discharge current of 5 A over 2 hours. In general, it can be said that a C-rate of n corresponds to the battery getting fully discharged in $1/n$ hours, irrespective of the battery capacity.

Battery efficiency

For designing PV systems it is very important to know the *efficiency* of the storage system. For storage systems, usually the *round-trip efficiency* is used, which is given as the ratio of the total storage output to the total storage input,

$$\eta_{\text{bat}} = \frac{E_{\text{out}}}{E_{\text{in}}}. \tag{19.28}$$

For example, if 10 kWh is pumped into the storage system during charging, but only 8 kWh can be retrieved during discharging, the round trip efficiency of the storage system is 80%. The round-trip efficiency of batteries can be broken down into two efficiencies: first, the *voltaic efficiency*, which is the ratio of the average discharging voltage to the average charging voltage,

$$\eta_V = \frac{V_{\text{discharge}}}{V_{\text{charge}}}. \tag{19.29}$$

This efficiency covers the fact that the charging voltage is always a little above the rated voltage in order to drive the reverse chemical (charging) reaction in the battery.

Secondly, we have the *coulombic efficiency* (or Faraday efficiency), which is defined as the ratio of the total charge extracted from the battery to the total charge put into the battery over a full charge cycle,

$$\eta_C = \frac{Q_{\text{discharge}}}{Q_{\text{charge}}}. \tag{19.30}$$

The *battery efficiency* then is defined as the product of these two efficiencies,

$$\eta_{\text{bat}} = \eta_V \cdot \eta_C = \frac{V_{\text{discharge}}}{V_{\text{charge}}} \frac{Q_{\text{discharge}}}{Q_{\text{charge}}}. \tag{19.31}$$

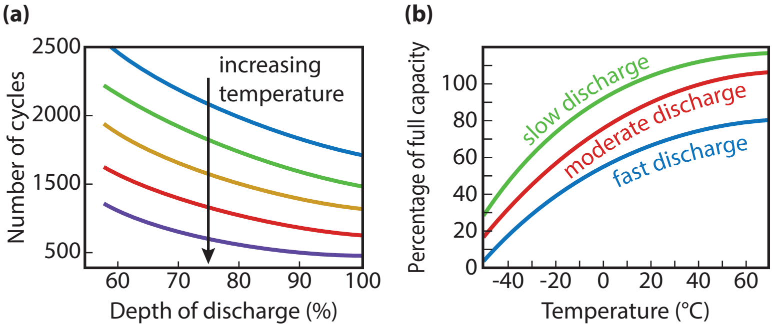

Figure 19.24: Qualitative illustration of (a) the cycle lifetime of a Pb-acid battery in dependence of the DoD and temperature and (b) effect of the temperature on the battery capacity (with kind permission from S. Bowden, Arizona State University) [155].

When comparing different storage devices, usually this round-trip efficiency is considered. It includes all the effects of the different chemical and electrical non-idealities occurring in the battery.

State of charge and depth of discharge

Another important battery parameter is the *State of Charge* (SoC), which is defined as the percentage of the battery capacity available for discharge,

$$\mathrm{SoC} = \frac{E_{\mathrm{bat}}}{C_{\mathrm{bat}} V}. \tag{19.32}$$

Thus, a 10 Ah rated battery that has been drained by 2 Ah is said to have a SoC of 80%. Also the *Depth of Discharge* (DoD) is an important parameter. It is defined as the percentage of the battery capacity that has been discharged,

$$\mathrm{DoD} = \frac{C_{\mathrm{bat}} V - E_{\mathrm{bat}}}{C_{\mathrm{bat}} V}. \tag{19.33}$$

For example, a 10 Ah battery that has been drained by 2 Ah has a DoD of 20%. The SoC and the DoD are complimentary to each other.

Cycle lifetime

The *cycle lifetime* is defined as the number of charging and discharging cycles after that the battery capacity drops below 80% of the nominal value. Usually, the cycle lifetime is specified by the battery manufacturer as an absolute number. However, stating the battery lifetime as a single number is a oversimplification because the different battery parameters discussed so far are not only related to each other but are also dependent on the temperature.

Figure 19.24 (a) shows the cycle lifetime as a function of the DoD for different temperatures. Clearly, colder operating temperatures mean longer cycle lifetimes. Furthermore, the cycle lifetime depends strongly on the DoD. The smaller the DoD, the higher the cycle lifetime. Thus, that the battery will last longer if the average DoD can be reduced during the lifetime of the battery. Also, *battery overheating* should be strictly controlled. Overheating can because of overcharging and subsequent over-voltage of the lead acid battery. To prevent this, charge controllers are used that we address in the next section.

Temperature effects

While the battery lifetime is increased at lower temperatures, another effect must be considered: the temperature affects the battery capacity during regular use too.

As seen from Fig. 19.24 (b), the lower the temperature, the lower the battery capacity. At higher temperatures, the chemicals in the battery are more active, leading to an increased battery capacity. At high temperatures, it is even possible to reach an above-rated battery capacity. However, such high temperatures are severely detrimental to the battery health. In Fig. 19.24 (b), it can be seen that the battery capacity increases when the discharge current is lower. This is because the discharge process in the battery is diffusion limited: if more time is allowed, a better exchange of chemical species between the pores in the plate and the electrolyte can take place.

Ageing

The major cause for ageing of the battery is *sulphation*. If the battery is insufficiently recharged after being discharged, sulphate crystals start to grow, which cannot be completely transformed back into lead or lead oxide. Thus the battery slowly loses its active material mass and hence its discharge capacity. *Corrosion* of the lead grid at the electrode is another common ageing mechanism. In case of lead-acid batteries *antimony poisoning* is a major cause for accelerated ageing [156]. Corrosion leads to increased grid resistance due to high positive potentials. Further, the electrolyte can *dry out*. At high charging voltages, gassing can occur, which results in the loss of water. Thus, demineralised water should be used to refill the battery from time to time.

19.3.4 Lead acid batteries used in PV applications

One can distinguish lead acid batteries based on the type of plates being used:

- In *flat-plate* lead-acid batteries the plates are significantly thicker than in the case of starter batteries implying a cycle life of 1000 cycles for a daily depth of discharge (DDOD) of 20% at 25 $\circ$ C.
- The positive plates of *tubular plate* lead-acid batteries are made of porous tubes, which contain the active mass. These tubes prevent the loss of active mass as a result of changes in volume, which occur in cyclic operation. The negative plates in tubular plate batteries are flat plates. The cycle life of this type of battery is considerable longer than that for batteries with flat plates described above. For real traction applications, such as in forklift trucks, tubular plates with a fairly high antimony content are used. These batteries have an excellent cycle life, but their self-discharge is far too high for most PV applications. For PV applications tubular plates are used with an antimony content such that the cycle life is still fairly good, but with a low