Efficiency of power converters

For planning a PV system it is very important to know the efficiency of the power converters. This efficiency of DC-DC and DC-AC converters is defined as

$$\eta = \frac{P_o}{P_o + P_d}, \tag{19.20}$$

i.e. the fraction of the output power P_o to the sum of P_o with the dissipated power P_d. For estimating the efficiency we thus must estimate the dissipated (lost) power, which can be seen as a sum of several components,

$$P_d = P_L + P_{\text{switch}} + P_{\text{other}}, \tag{19.21}$$

i.e. the power lost in the inductor P_L, the power lost in the switch, and other losses. P_L is given as

$$P_L = I_{L,\,\text{rms}}^2 R_L, \tag{19.22}$$

where $I_{L,\,\text{rms}}$ is the mean current flowing through the inductor. The losses in the switch strongly depend on the type of switch that is used. Other losses are for example resistive losses in the circuitry in-between the switches.

For a complete inverter unit it is convenient to define the efficiency as

$$\eta_{\text{inv}} = \frac{P_{\text{AC}}}{P_{\text{DC}}}, \tag{19.23}$$

which is the ratio of the output AC power to the DC input power. Figure 19.18 shows the efficiency of a commercially available inverter for different input voltages. As we can see, in general the lower the output power, the less efficient the inverter. This is due to the power consumed by the inverter (self-consumption) and the power to control the various semiconductor devices which is relatively high at low output power. This efficiency characteristic must be taken into account when planning a PV system. Further, the efficiency is lower if the input voltage deviates from the nominal value. Indeed up and down conversion losses become somewhat larger among others as more energy is stored in the inductors.

19.3 Batteries

In this section we discuss a vital component not only of PV systems but of renewable energy systems in general. *Energy storage* is very important at both small and large scales in order to tackle the intermittency of renewable energy sources. In the case of PV systems, the intermittency of the electricity generation is of three kinds: first, *diurnal* fluctuations, *i.e.* the difference of irradiance during the 24 hour period. Secondly, fluctuations from one day to another because of changes of weather, especially changes in the cloud coverage. Thirdly, the *seasonal* fluctuations, *i.e.* the difference of irradiance between the summer and winter months. There are several technological options for realising storage of energy. Therefore it is important to make an optimal choice.

Fig. 19.19 shows a *Ragone* chart, where the *specific energy* is plotted against the *peak power density*. Because it uses a double-logarithmic chart storage technologies with very

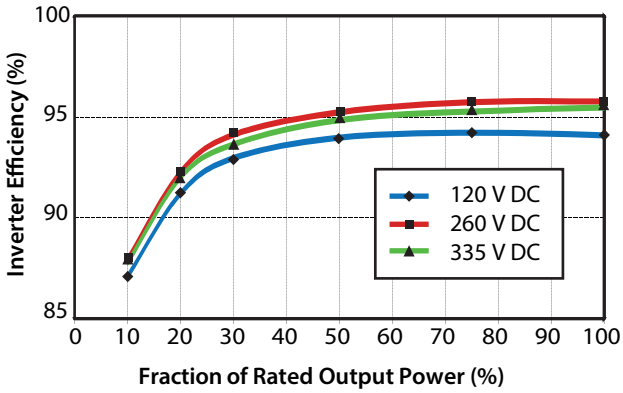


Figure 19.18: The power-dependent efficiency for several input voltages of a *Fronius Galvo 1.5-1 208-240* inverter at 240 V AC. The nominal input voltage is 260 V DC. (Data taken from Ref. [154] and used with kind permission from California Energy Commission).

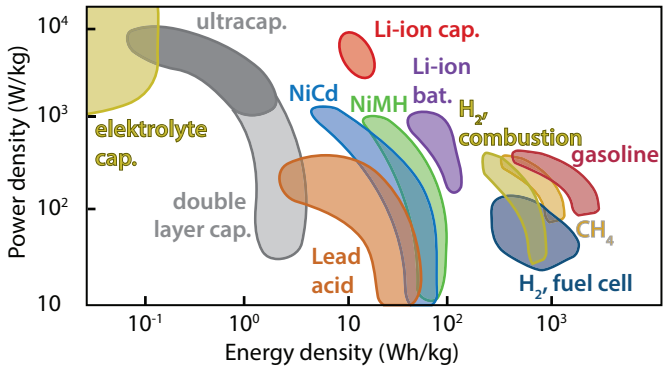


Figure 19.19: A *Ragone* chart of different energy storage methods. Capacitors are indicated with "cap".

different storage properties can be compared in one plot. Solar energy application require a high energy density and – depending on the application – also a reasonably high power density. For example, we cannot use capacitors because of their very poor energy density. For short term to medium term storage, the most common storage technology of course is the *battery*. Batteries have both the right energy density and power density to meet the daily storage demand in small and medium-size PV systems. However, the seasonal storage problem at large scales is yet to be solved.

The ease of implementation and efficiency of the batteries is still superior to that of other technologies, like pumping water to higher levels, compressed air energy storage, conversion to hydrogen, flywheels, and others. Therefore we will focus on battery technology as a viable storage option for PV systems.

Batteries are electrochemical devices that convert chemical energy into electrical energy. We can distinguish between primary or secondary batteries. Primary batteries convert chemical energy to electrical energy *irreversibly*. For example, *zinc carbon* and *alkaline* batteries are primary batteries.

Secondary batteries or *rechargeable batteries*, as they are more commonly called, convert chemical energy to electrical energy *reversibly*. This means that they can be recharged when an over-potential is used. In other words, excess electrical energy is stored in these secondary batteries in the form of chemical energy. Typical examples for rechargeable batteries are *lead acid* or *lithium ion* batteries. For PV systems only secondary batteries are of interest.

19.3.1 Types of batteries

Lead-acid batteries are the oldest and most mature technology available. They will be discussed in detail later in this section.

Other examples are *nickel-metal hydride* (NiMH) and *nickel cadmium* (NiCd) batteries. NiMH batteries have a high energy density, which is comparable to that of lithium-ion batteries (discussed below). However, NiMH batteries suffer from a high rate of self discharge. On the other hand, NiCd batteries have much lower energy density than lithium ion batteries. Furthermore, because of the toxicity of cadmium, NiCd batteries are widely banned in the European Union for consumer use. Additionally, NiCd batteries suffer from what is called the *memory effect*: the batteries loose their usable energy capacity if they are repeatedly charged after only being partially discharged. These disadvantages make NiMH and NiCd batteries unsuitable candidates for PV storage systems.

Lithium ion batteries (LIB) and *lithium-ion polymer* batteries, which are often referred to as lithium polymer (LiPo) batteries, have been heavily investigated in recent years. Their high energy density already has made them the favourite technology for light-weight storage applications for example in mobile telephones. However, these technologies still suffer from high costs and low maturity.

The last and the most recent category of batteries that we will discuss in this treatise are *redox-flow* batteries. Lead-acid batteries and LIB, the two main storage options for PV systems, are similar in the sense that their electrodes undergo chemical conversion during charging and discharging, which makes their electrodes to degenerate with time, leading to inevitable “ageing” of the battery. In contrast, redox flow batteries combine properties of both batteries and fuel cells, as illustrated in Fig. 19.20. Two liquids, a *positive electrolyte*

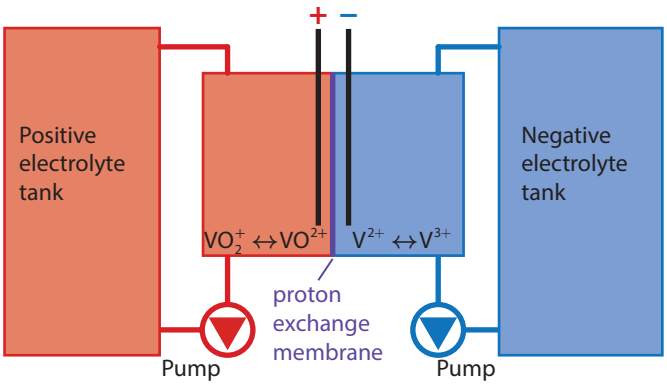


Figure 19.20: Schematic on a *vanadium* redox-flow battery that employs vanadium ions.

and a *negative electrolyte* are brought together only separated by a membrane, which only is permeable for protons. The cell thus can be charged and discharged without the reactants being mixed, which in principle prevents the liquids from ageing. The chemical energy in a redox flow battery is stored in its 2 electrolytes, which are stored in two separate tanks. Since it is easy to make the tanks larger, the maximal energy that can be stored in such a battery thus is not restricted. Further, the maximal output power can easily be increased by increasing the area of the membrane, for example by using more cells at the same time. The major disadvantages is that such a battery system requires additional components such as pumps, which makes them more complicated than other types of batteries.

Figure 19.21 shows a Ragone plot as it is used to compare different battery technologies. In contrast to Fig. 19.19, here the the gravimetric energy density and volumetric energy density are plotted against each other. The *gravimetric energy density* is the amount of energy stored per mass of the battery; it typically is measured in Wh/kg. The volumetric energy density is the amount of energy stored per volume of battery; it is given in Wh/l. The higher the gravimetric energy density, the lighter the battery can be. The higher the volumetric energy density, the smaller the battery can be.

Figure 19.21 shows that lead-acid batteries have both the lowest volumetric and gravimetric energy densities among the different battery technologies. Lithium ion batteries show ideal material properties for using them as storage devices. Redox-flow batteries are very promising. However, both LIB and redox-flow batteries are still in a development phase which makes these technologies still very expensive. Thus, because of to the unequalled maturity and hence low cost of the lead-acid batteries, they are still the storage technology of choice for PV systems.

Figure 19.22 shows a sketch of a lead-acid battery. A typical battery is composed of several individual cells, of which each has a nominal cell voltage around 2 V. Different methods of assembly are used. In the *block assembly*, the individual cells share the housing and are interconnected internally. For example, to get the typical battery voltage of 12 V, six cells are connected in series. As the name suggests, lead-acid batteries use an acidic electrolyte, namely diluted sulphuric acid H_2SO_4. Two plates of opposite polarity are inserted in the electrolyte solution, which act as the electrodes. The electrodes contain grid

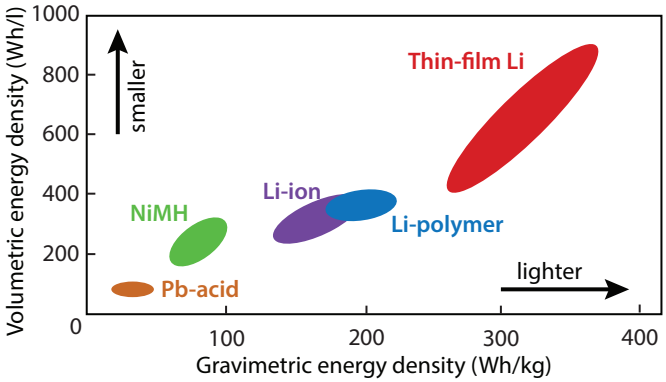


Figure 19.21: A Ragone chart for comparing different secondary battery technologies with each other.

shaped lead carrier and porous active material. This porous active material has a sponge-like structure, which provides sufficient surface area for the electrochemical reaction. The active mass in the negative electrode is lead (Pb), while in the positive electrode lead dioxide (PbO_2) is used. In the figure, also the chemistry of charging and discharging the battery is shown.

When the battery is discharged, electrons flow from the negative to the positive electrode through an external circuit, causing a chemical reaction between the plates and the electrolyte. This forward reaction also depletes the electrolyte, affecting its *state of charge* (SoC). When a source with a voltage higher than the actual battery voltage is connected to the battery, the reverse reaction is enabled. Then, the flow of electrons is reversed and the battery is recharged. In a PV systems, this source is nothing but the PV module or array. In grid-connected systems, also the inverter operating as a AC-DC converter can be used to charge the battery.

19.3.2 Equivalent circuit

To understand how a battery works, it is important to look at the equivalent circuit. As we can see from Fig. 19.23 (a), a simple representation of the equivalent circuit is given by a voltage source with a constant voltage $V_{\text{OC-BB}}$ and an internal resistance R_i. The subscript BB denotes *battery bank*. In reality, $V_{\text{OC-BB}}$ will not be constant, but a function of the state of charge (SoC, see below), the ambient temperature, and others,

$$V_{\text{OC-BB}} = f(\text{SoC}, T, \ldots). \tag{19.24}$$

For the discussions in this book, we will neglect these dependencies.

Because of R_i, the voltage V_{BB} will differ from $V_{\text{OC-BB}}$. In fact, V_{BB} is also dependent on the current I_{BB} flowing through the battery, as seen by the equation

$$I_{\text{BB}} = \frac{1}{R_i}\left(V_{\text{BB}} - V_{\text{OC-BB}}\right). \tag{19.25}$$

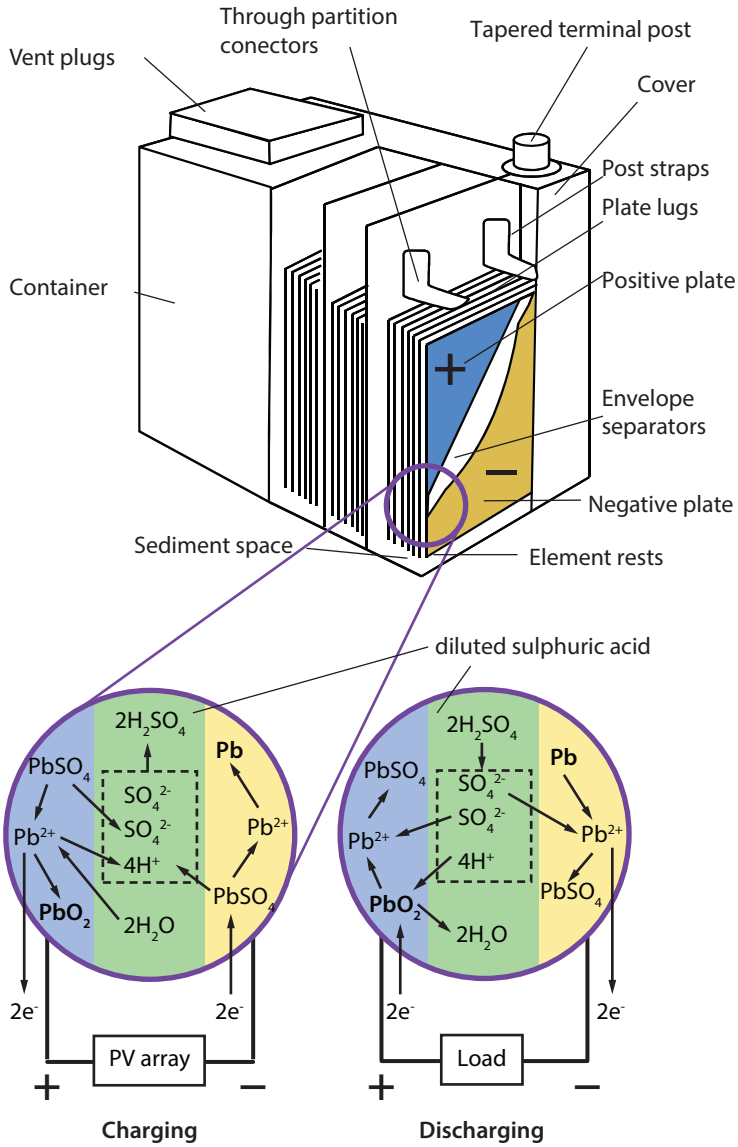


Figure 19.22: Schematic of a lead-acid battery and the chemistry of charging and discharging.

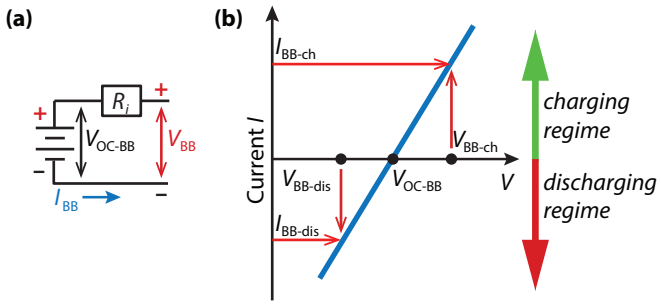


Figure 19.23: A simple model for (a) the equivalent circuit and (b) the *I-V* characteristics of a battery.

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,

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

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,