this is an irreversible effect and destroys the double capacitor. An additional problem is that in many double-layer capacitors aqueous electrolytes are used and the gassing must be avoided as well (start of water electrolysis at 1.23 V). Therefore, the maximum voltage needs to be limited to approximately 1.5 to 2.0 V. To avoid the electrolysis problem, organic electrolytes are used which allow maximum voltages of 3 to 4 V, but they have significantly lower conductivity than aqueous electrolytes. Therefore, for applications with very high power requirements capacitors with aqueous electrolytes are used; if higher energy density and lower power is required organic electrolytes can be used. Because overcharging of the double-layer capacitors will destroy them, a careful single-cell control is necessary when they are operated in long strings of series-connected cells.

Double-layer capacitors are often known by their brand names like SuperCaps or GoldCaps. They all are based on the above-described technology.

The self-discharge of double-layer capacitors is in the range of 5%/day at 20°C. Especially at higher temperatures, the self-discharge rate (approximately doubling of the self-discharge rate with a 10-K temperature increase as in all electrochemical systems) is hardly acceptable for autonomous power supply systems.

The electrical characteristics are dominated on one hand by the low inner resistance (resulting in high power) and on the other hand by the linear decrease in voltage with the state of charge. On one hand, this allows easy estimation of the state of charge, but on the other hand the voltage drop is very high and increases the requirements of the electronics or limits the usable energy from the double-layer capacitor (e.g. operation only between 1.7 and 2 volts).

Today, double-layer capacitors are available in units of up to some thousand farads. Their gravimetric and volumetric energy density is very low (Figure 18.7), but they may have power densities up to 5000 W/kg. Therefore, double-layer capacitors are most suited to applications with very high power requirements and low energy demand. As double-layer capacitors are a new and emerging technology, it is difficult to give definite cost figures. For orientation purposes, a cost of approximately 50 000 euro/kWh can be estimated today. However, to supply a current of 200 A at 2 V for 2 seconds the cost is approximately 10 euro for the storage.

For autonomous power supply systems, double capacitors are an interesting technology in applications with peak power demand or for smoothing of power flow. These are, for example, pumping systems where pumps have a very high power demand to overcome the initial inertia. Another application might be grid-connected PV inverters with power quality control functionality. They are more efficient with a milli second storage system. As a rule of thumb, it can be assumed that double-layer capacitors can find their place in applications with discharge times of less than 10 s per cycle (for "power storage") or in combinations with conventional batteries. The big advantage of the capacitors is their almost unlimited number of cycles until the end of their lifetime (several hundred thousands).

18.4.7 The Lead Acid Battery

Lead acid batteries have been commercially used for more than 100 years for storing electrical energy. It has been the most widely used storage system for electrical energy