on the temperature, the alloy and the state of charge. For outdoor applications, it is important to be aware that the pressure in the metal-hydride tank at constant hydrogen load approximately doubles with an increase of 20 K in temperature.

The energy content of 1 Nm^3 of hydrogen gas is approximately 3.5 kWh. Depending on the fuel cell system and power-converter efficiency, between 1 and 1.8 kWh of net energy can be drawn from 1 Nm^3 of hydrogen gas.

A standard 200 bar pressure bottle contains 8.8 Nm^3 of hydrogen gas. The cost for metal-hydride storage systems is currently in the range of 500 to 1500 € per Nm^3.

For oxygen storage, currently only pressure tanks are commercially available. Materials with adsorption properties for oxygen are under investigation. A reduction in volume by a factor of 3 has been achieved.

Nanotubes for hydrogen storage are under investigation. After a very optimistic period some years ago, the optimism has been reduced, but meanwhile there are several activities to investigate this technology which promises very low costs.

18.5.2.3 Fuel cell

As fuel cells can only replace batteries in conjunction with the hydrogen gas generation, only the polymer electrolyte or proton exchange membrane fuel cell (PEMFC) is considered here. A very comprehensive overview of all the fuel cell technologies is given in [36].

The basic reactions are given in equations (18.17) and (18.18).

Anode reaction $$H_2 \rightarrow 2H^+ + 2e^- \tag{18.17}$$

Cathode reaction $$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{18.18}$$

Figure 18.29 shows a schematic of a PEM fuel cell. If hydrogen and oxygen are stored, a closed-loop operation with water and gases can be realised. Then, the water demand for refilling is limited. If air is used instead of pure oxygen, the water produced in the fuel cell process gets lost with the air throughput. The water household of the membrane is one of the most challenging problems in fuel cell operation and control.

PEMFCs operate best at temperatures between 60 and 90°C. The fuel cell stack itself can operate at an efficiency of 50 to 60%. The overall fuel system has additional components beside the stack like air compressors, electronics, valves and security devices. They cause a self-consumption of the fuel cell system and therefore reduce the overall efficiency to 35 to 50%. The efficiency is higher if pure oxygen is used instead of air, but this requires an additional oxygen tank. The stack efficiency is calculated from the ratio of the fuel cell voltage during power generation and the electrochemical potential of the reactants, which is 1.23 V. The coulomb efficiency is considered as 100% even though some gas losses synonymous with coulomb losses due to the penetration of gas through the membrane occur as well.

A big advantage of fuel cells in comparison with motor generators are the high efficiency even at partial loads. Usually the stack efficiency increases with decreasing power output.