Chapter 5
Storage Technologies and Systems

5.1 Overview

Energy storage systems have been instrumental in the modernization of our society. Energy storage systems have been essential for decoupling electricity generation from consumption since electrification began. Their use will grow yet more predominant in the future; the greatest amount of electricity is being generated by volatile renewable-energy sources, such as wind and solar power. This will entail the use of new solutions to optimally decouple the power generated by renewables from the power demanded. Multi-energy systems and virtual-power plants constitute the most promising solutions; both of them employ energy storage systems as well as demand-side and demand-response programs.

The power exchanged with the bordering country is decisive for balancing the power generated by renewable-energy sources (see Fig. 5.1).

Demand-side and demand-response programs integrate consumers actively in the balancing of electric power. Energy storage systems make it possible to convert electricity into other forms of energy and to store it. The stored power is generally successively reconverted into electricity and supplied to the grid (see Fig. 5.2). The power stored in multi-energy systems can be released in a different form than its original one, for example, in power-to-gas or power-to-heat storage solutions. A power-to-gas system converts electricity into gas (hydrogen and/or methane) and supplies it to the natural gas infrastructure (pipelines, caverns and tanks). A power-to-heat system converts electricity into hot water, steam or even ice and delivers it to the thermal infrastructure (pipelines and storage).

Electricity can be converted and stored in a variety of other forms. Potential, kinetic, mechanical, thermal and chemical storage systems are used predominantly. Pumped-hydroelectric storage is the most advanced technology. This technology has been developed in parallel with hydropower plants in Europe in order to use hydropower reserves better also in periods of low rainfall. The use of nuclear power has increased the need for energy storage systems. This has entailed the construction of new pumped-storage plants. They are the sole solution for decoupling the

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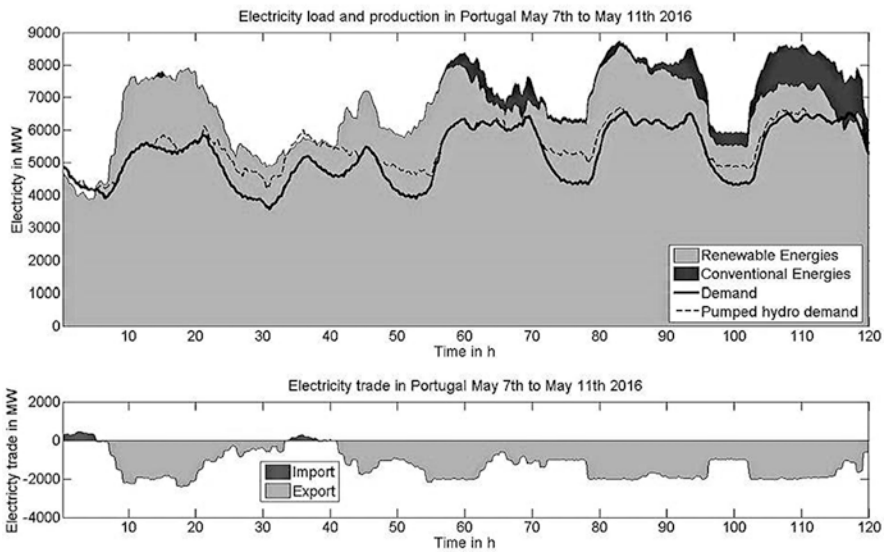


Fig. 5.1 supply of power by renewables in Portugal in May, 2016.

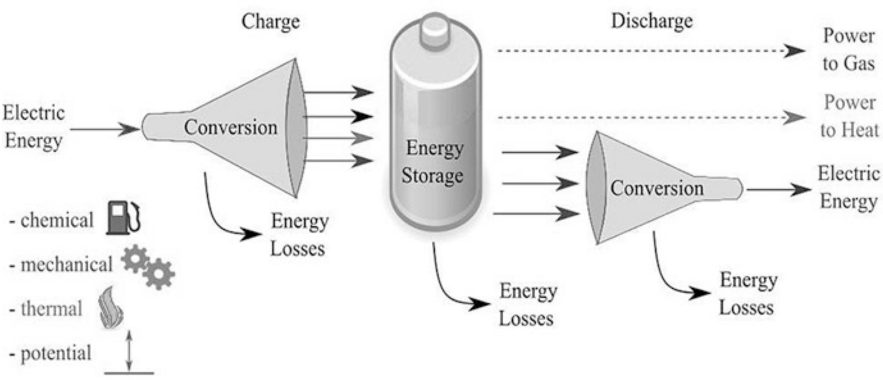


Fig. 5.2 The energy-storage process

power generated by nuclear power plants from electrical loads. Large pumped storage plants store power at night (when low electricity prices exist), thus, enabling nuclear power plants to work continuously near their nominal value. The stored power is gradually released during the peak hours during the day (when high electricity prices exist). Consequently, pumped-storage plants are also used as peak-power plants.

In addition to this first option, electricity can also be stored as kinetic energy by using flywheels. Flywheels are one of the oldest energy storage systems to be used by mankind (see Fig. 5.3). They were largely used in the production of ceramics by

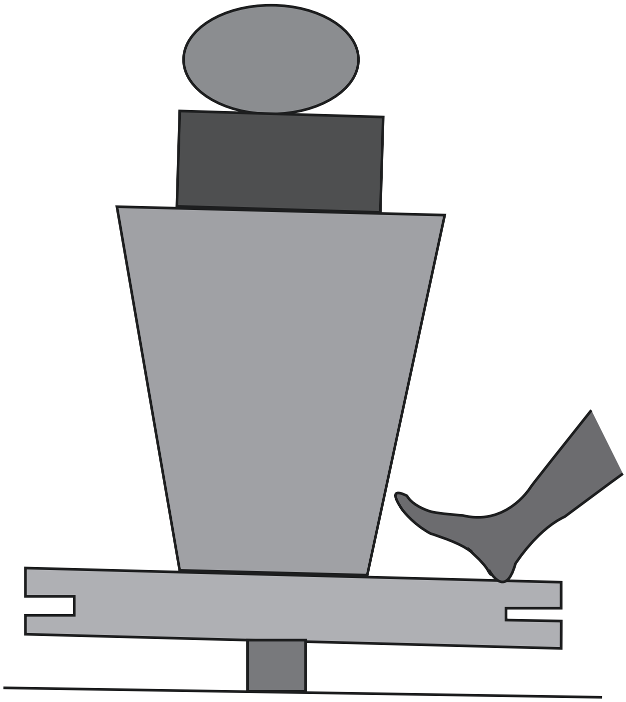


Fig. 5.3 Ptolemaic potter's wheel

constantly accumulating the angular velocity of the potter. Flywheels are now being used in many applications, ranging from automotive to aerospace systems. They are mostly used in electrical grids to supply power to uninterruptible loads and to control an electrical grid's frequency.

Compressed air is another (mechanical) form of electricity storage. Two diabatic compressed-air energy storage (CAES) systems are in operation worldwide. The first diabatic CAES in Huntorf, Germany, commenced operation at the end of 1978. It was the first energy storage plant installed on flat terrain. Its main function was to cover the peak-hour demand for power. A more efficient diabatic CAES system in McIntosh, Alabama, USA, commenced operation in 1991. Both convert electricity into compressed air, which is stored in underground caverns. The heat generated during the compression phase is released into the air. During the discharge phase, the compressed air is warmed inside a combustor and then expands inside a turbine that drives an electric generator. Such energy storage systems store and release large quantities of power (in the range of megawatts) for various time periods. Similar to pumped-hydroelectric storage (PHS) systems, CAES systems have geographic constraints as compressed air has to be stored in caverns.

Unlike energy storage systems that convert electricity into potential and mechanical energy, thermal-storage systems are unidirectional. Rather than being reconverted into electricity, the stored energy is supplied as steam, hot water or ice. Such (seasonal) storage systems store energy long-term. They are used mainly in industrial processes and for the heating and cooling of rooms. They are easily coupled with demand-side management programs at industrial parks.

Electricity converted into chemical form (i.e., hydrogen or methane) can be stored for a long time. Such (power to gas) solutions utilize the entire natural-gas infrastructure (pipelines, caverns, compression stations and tanks). The storage systems can discharge the electricity stored as either heat or electricity. Combined heat and power plants release a combination of heat and power. It is also a solution for transportation, as a variety of combustion engines have been designed to burn methane.

Apart from gas, batteries are another solution that stores electricity chemically. Experience acquired in the electronic-devices sector has helped enhance the performance of battery systems. More and more large battery plants (in the MW domain) have been connected to the grid in recent years. Batteries and gas are also solutions for green transportation. Unlike gasoline-powered models, however, electric vehicles can support the grid when they are connected to it, thus becoming an added resource for grid operators.

5.2 Energy-Storage Performance Indicators

Energy storage systems can be compared and classified technically using key performance indicators. The main indicators used are listed in the Table 2.3. Below three of them, which are used for general storage descriptions, are described in detail.

Round-trip efficiency is the most common one. It describes the losses measured during the charging, discharging and standby phases (see Eq. (5.1)). It is the ratio of the output energy to the input energy. High round-trip efficiency means low energy losses. The energy losses may be of different natures. Generally they are in form of heat and are released into the surrounding environment.

$$\eta = \frac{E_{out}}{E_{in}} \tag{5.1}$$

The state of charge (SOC) represents the amount of energy (E(t)) that can be withdrawn from or stored in an energy storage system over a specific time (t). The SOC is usually related to the maximum storable energy (E_{max}) and is specified as a percentage: A 100 % SOC is a fully- charged energy storage system, while a 0 % SOC is an empty one (see Eq. (5.2)).

$$SOC(t) = \frac{E(t)}{E_{max}} \cdot 100 \tag{5.2}$$

The depth of discharge (DoD) is the ratio of the maximum amount of energy that could be discharged from an energy storage system to the maximum storable energy

(E_{max}). It is usually specified as a percentage: A 100 % DoD indicates that the energy storage system can discharge all of the energy stored (see Eq. (5.3)).

$$DoD = \frac{E_{disch\_max}}{E_{max}} \cdot 100 \tag{5.3}$$

5.3 Electric-Energy Storage System Classification

Energy storage systems are generally classified according to two criteria: power rating and rated energy capacity (see Fig. 5.4). Using these criteria, three application domains can be identified: power quality, bridging power and energy management. Energy storage systems for power quality have to be able to charge and discharge electricity within short periods of times (i.e., minutes). The power rating and energy capacity is slightly higher for bridging power, while power rating and rating capacity are much higher for energy management. Rating power can reach the GW range and capacity covering days to months. Energy storage systems can additionally be classified as short-term (for power quality and bridging power) or long-term (for energy management) storage systems.

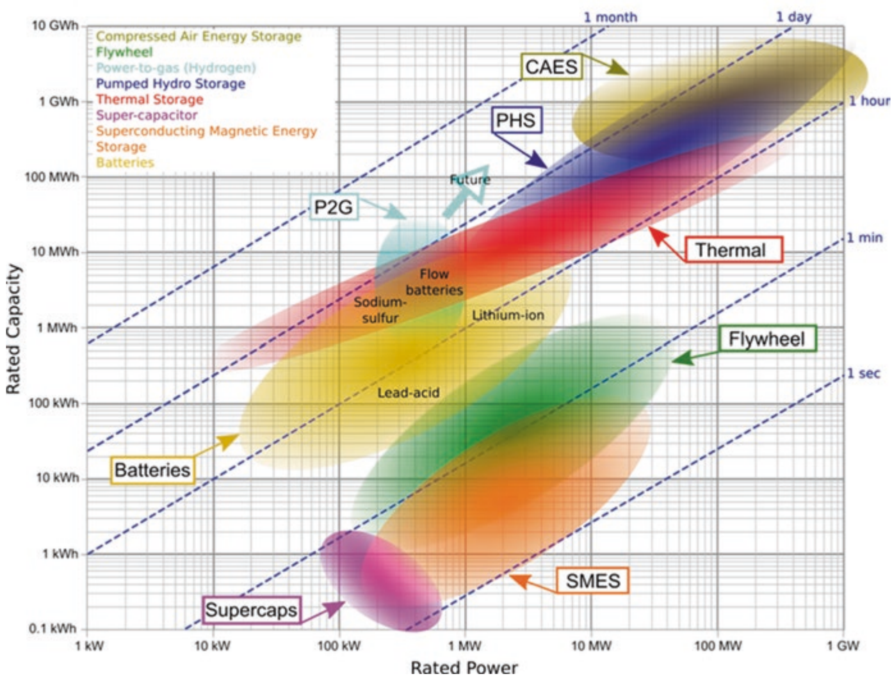


Fig. 5.4 Classification of energy storage applications

The most suitable energy storage technologies for power quality are supercapacitors, superconducting magnetic-energy storage (SMES) systems, flywheels and batteries. Some batteries, for example, sodium-sulfur, lithium-ion and flow batteries, can be also used for bridging power and energy management. Compressed air energy storage, PHS and power to gas systems are energy management applications.

5.4 Pumped-Hydroelectric Storage

Pumped-hydroelectric storage systems are the most advanced energy storage technology worldwide. More than 170 GW are currently in operation. Such energy storage systems store electricity as potential hydraulic energy. During the charge phase, a water system pumps water from a low-level reservoir to a higher-level reservoir. During the discharge phase, the water returns to the lower reservoir, passing through turbines that drive electric generators. As pictured in Fig. 5.5, PHES systems usually consist of an upper reservoir, penstocks, a turbine, a generator, a pump, a motor, a lower reservoir and a connection to the electric grid. There are two main types of PHES facilities: Pure (closed loop) PHES, in which the water pumped into the upper reservoir is the only source of the storage plant, and the hybrid v, in which both the pumped water and natural stream-flow water flow into the turbine to generate electricity.

This technology's round-trip efficiency ranges 70–85 %. The main losses are caused by friction, turbulence and viscous drag inside the turbine, pump and penstocks. Other losses are also caused by the water's kinetic energy, which is not fully recovered in the turbine, and losses of electricity in the generator and motor. A PHES system's efficiency can be calculated with Eq. (5.4), in which ξ_t represents the turbine's overall efficiency and ξ_p the pump's efficiency.

$$\eta = \frac{E_{out}}{E_{in}} = \frac{E_t}{E_p} = \xi_t \cdot \xi_p \tag{5.4}$$

The energy consumed by the pump during charging (E_p) can be calculated with Eq. (5.5) and depends on:

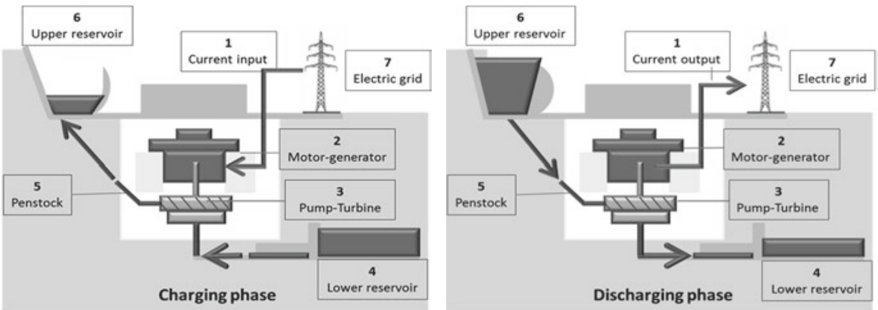


Fig. 5.5 Pumped-hydroelectric storage: charging (*left*) and discharging (*right*)

- the volume of water pumped (V);
- the elevation (h) up to which the water has to be pumped;
- the pump's overall efficiency (ξ_p); and
- the water density (ρ).

$$E_p = \frac{\rho g h V}{\xi_p} \tag{5.5}$$

The energy generated by the turbine (E_t) and fed into the electric grid can be calculated with Eq. (5.6):

$$E_t = \rho g h V \xi_t. \tag{5.6}$$

The maximum speed (v) of the mass (m) of the water entering the turbine depends on the elevation (h) of the upper reservoir. It can be calculated by matching its potential energy (W_{pot}) with the kinetic energy (W_{kin}) (see Eqs. (5.7) and (5.8)) it attains at the turbine inlet. It can be evaluated with Eq. (5.9).

$$W_{kin} = W_{pot} \tag{5.7}$$

$$\frac{1}{2} m v^2 = W_{pot} = mgh \tag{5.8}$$

$$v_{max} = \sqrt{2gh} \tag{5.9}$$

The first PHS plants were installed in the alpine regions of Italy and Switzerland at the end of nineteenth century. They were comprised of two units, the motor-pump and the generator-turbine, which were mounted on two separate shafts. Such a scheme is rarely utilized today because of the high capital expenditure required. Reversible binary and ternary machine schemes are most frequently used instead. A reversible binary machine consists of a single reversible pump/turbine and motor/generator unit mounted on the same shaft (see Fig. 5.6 left). The pump-generator can operate either as a pump or as a turbine, depending on its direction of rotation. The advantage of such a scheme is the capital expenditure required, and the disadvantage is its lower overall efficiency. A variable-speed generator motor can be utilized to increase efficiency. It can be an asynchronous or synchronous motor-generator with a frequency converter. Its use raises the pump's rotational speed and extends the turbine's operating range. A torque converter can be used to start pumping without disrupting the system voltage.

The ternary unit consists of a motor-generator, a turbine and pump on the same shaft mounted vertically or horizontally (see Fig. 5.6 right). Such a configuration is roughly 20 % more expensive, but also more efficient than a binary one. Francis and Pelton turbines are normally used. Francis turbines are designed for water heads of up to 700–800 meters, and Pelton turbines cover larger heads. The machine is

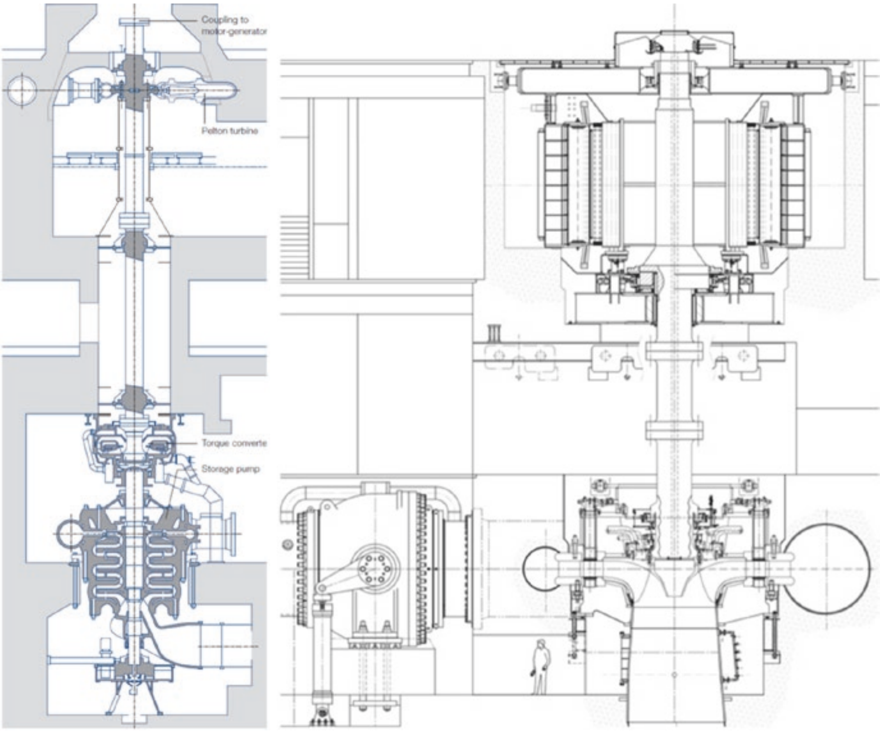


Fig. 5.6 Reversible binary machine (*left*) and a ternary system (*right*) [1]

started by activating the pump, and the load is subsequently progressively transferred to the motor-generator. Both the turbine and the pump can be regulated from 0 to 100 % of unit output.

The highest pumped-hydropower capacity is installed in Japan, China and the USA, respectively (see Table 5.1). Apart from orographic reasons, the main motive for the use of PHES in these countries is the decoupling of power generated by nuclear power plants from loads. The world´s first 30 MW-seawater PHS system has been in operation in Okinawa, Japan, since 1999 (see Fig. 5.7). Using the sea as its lower reservoir, It pumps seawater to an upper reservoir 150 meters above sea level.

5.5 Flywheel-Energy Storage

A flywheel system stores electricity as kinetic energy. Its capacity to store energy depends on its rotating mass, shape and rotational speed. The rotating mass is connected to a motor-generator that causes the flywheel to accelerate (when charging) and to decelerate (when discharging). When the flywheel is not in use, it idles at its idle speed. Flywheels generally consist of a cylindrical rotor or dish (mechanical

Table 5.1 Pumped-hydroelectric storage capacity installed worldwide [3]

Country	Installed capacity [MW]	Country	Installed capacity [MW]	Country	Installed capacity [MW]
Japan	27,438	Poland	1745	Lithuania	900
China	21,545	Portugal	1592	Philippines	709
USA	20,858	South Africa	1580	Greece	699
Italy	7071	Thailand	1391	Serbia	614
Spain	6889	Belgium	1307	Morocco	465
Germany	6388	Russia	1246	Ireland	292
France	5894	Czech Republic	1145	Croatia	282
India	5072	Luxembourg	1096	Slovenia	185
Austria	4808	Bulgaria	1052	Canada	174
Korea, South	4700	Iran	1040	Romania	53
United Kingdom	2828	Slovakia	1017	Chile	31
Switzerland	2687	Argentina	974	Brazil	20
Taiwan	2608	Norway	967		
Australia	2542	Ukraine	905		

Fig. 5.7 Seawater pumped-hydropower plant in Okinawa, Japan [2]

or magnetic), bearings, a motor-generator and power electronics enclosed inside a low-pressure vacuum (see Fig. 5.8). The vacuum reduces the aerodynamic friction between the flywheel and the air. The use of magnetic bearings affects efficiency similarly. Flywheels can have a round-trip efficiency of more than 80 % and self-discharge of less than 3 %/hour. Superconducting magnetic bearings can

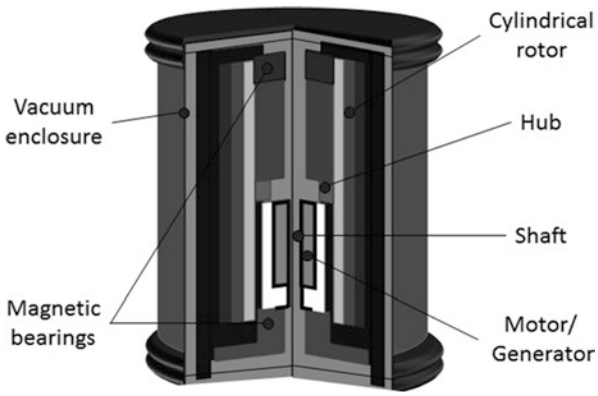


Fig. 5.8 Model high-speed flywheel

reduce self-discharge to less than 0.5 %/hour, but require higher capital expenditure. Flywheels are generally classified into two categories: low-speed and high-speed. Low-speed flywheels are usually made of metals such as steel and have mechanical bearings. They have an operating angular velocity in the range of 6000 rpm. High-speed flywheels are made from composites and have magnetic bearings. They have an operating angular velocity in the range of 100,000 rpm.

As mentioned above, flywheels store electricity as kinetic energy. If J is the moment of inertia of a mass (m) rotating with an angular velocity (ω), then the stored energy can be calculated by Eq. (5.10):

$$E = \frac{1}{2} J \omega^2. \tag{5.10}$$

The moment of inertia is a function of the mass and the shape of the mass. It can be calculated by Eq. (5.11):

$$J = \int x^2 dm_x. \tag{5.11}$$

where x is the distance of the differential mass (dm_x) from the rotating axes. The moment of inertia of a flywheel with its mass m concentrated at the edge of the radius (r) is calculated by Eq. (5.12):

$$J = \int x^2 dm_x = mr^2. \tag{5.12}$$

The maximum energy that a flywheel can store depends on its material, which determines the upper angular velocity. A rotating mass is subject to tensile stress. The tensile stress (σ) of a flywheel with its mass (m) concentrated at the edge of the radius r is calculated by Eq. (5.13):

$$\sigma = \rho r^2 \omega^2 \tag{5.13}$$

where ρ is the density of the material. When the maximum tensile stress (σ_{max}) of the material is known, then the maximum angular velocity (ω_{max}) is also known. The maximum stored energy is calculated by Eq. (5.14):

$$E_{max} = \frac{1}{2} m \frac{\sigma_{max}}{\rho}. \tag{5.14}$$

Along with the maximum storable energy, knowledge of the specific energy per unit mass (E_m) is also important. It is calculated by Eq. (5.15). Table 5.2 presents the tensile strength and the maximum specific energy density for different materials.

$$E_m = \frac{1}{2} r^2 \omega^2 \tag{5.15}$$

The minimum, operating angular speed depends on the drivetrain torque (T). When power (P) is constant, the angular speed drops when the drivetrain torque (T) increases (see Eq. (5.16)):

$$P = T\omega. \tag{5.16}$$

The higher the angular velocity is, the more energy is stored. Given the limitation on the drivetrain torque, the speed ratio, i.e., the ratio between the minimum and the maximum operating angular velocity ($s = \omega_{min}/\omega_{max}$), is usually never lower than 0.2. The useful stored energy is calculated with Eq. (5.17):

$$E = \eta_{st} E_{max} \left(1 - s^2\right). \tag{5.17}$$

Figure 5.9 shows the correlation between the discharge energy and the speed ratio. Slowing down the angular velocity up to 50 % of its maximum value, the discharged energy is about 75 % of the nominal value. It means that the DoD in this case is 75 %.

A single flywheel generally has an energy storage capacity which ranges from 0.25 to 6 kWh. The storage capacity increases if more flywheels are connected in parallel. Currently, some companies are commercializing flywheel systems with a storage power of 20 MW and an energy storage capacity of 5 MWh (15 min at maximum rated power).

Table 5.2 Data on various rotor materials [4]

Material	Density [kg/m³]	Tensile strength [MPa]	Maximum specific energy density [kWh/kg]
Monolithic material: 3040 steel	77,000	1520	0.05
Composites			
E-glass	2000	100	0.014
S2-glass	1920	1470	0.21
Carbon T1000	1520	1950	0.35
Carbon AS4C	1510	1650	0.30

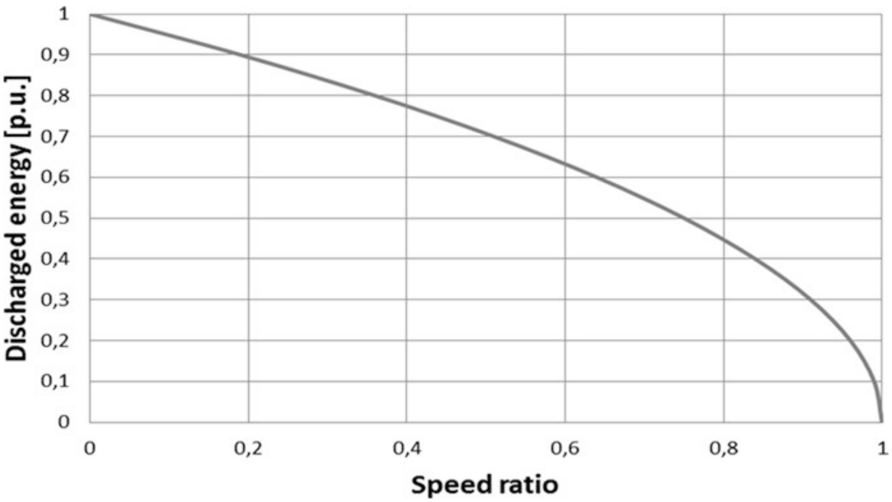


Fig. 5.9 Correlation between discharged energy and speed ratio

The flywheels in power systems currently in use are employed mostly for power applications (rapid charge and discharge), such as frequency control. A demonstration project in 2008 tested the use of a 1 MW (250 kWh) flywheel system for frequency regulation in the Independent System Operator New England electric grid. A larger flywheel (20 MW, 5 MWh) has been in operation in the New York ISO grid since 2011. Table 5.3 summarizes the main performance characteristics of flywheels.

5.6 Battery-Energy Storage Systems

Battery-energy storage systems are the most established energy storage technology. They are classified as primary or secondary batteries, the main difference being the recharging capability. Primary batteries can only be discharged. Since secondary

Table 5.3 Main performance indicators of flywheels [5]

Indicator	Value
Power footprint [kW/m²]	1.4–490
Energy footprint [kWh/m²]	0.35–0.54
Round trip efficiency	80–90 %
Standby energy loss [h^{-1}]	1–3 %
Ramp rate [sec^{-1}]	>25 %
Operational life [cycles]	>100,000

batteries can be charged and discharged many times, only they can be labeled as energy storage systems.

The main components of batteries are the electrodes (anode and cathode), the electrolyte and the external circuit. The electrodes and the electrolyte may be made of solid or liquid materials. The electrodes have contact with the electrolyte. During discharge, the anode supplies positive ions (cations) to the electrolyte, thus, oxidizing and charging itself with electrons (see Eq. (5.18)). At the same time, the cathode receives electrons through the external circuit and reduces itself (see Eq. (5.19)). It also receives positive ions from the electrolyte and supplies negative ions (anions) to the electrolyte.

$$E(A)_{red} \rightarrow E(A)_{ox} + n \cdot e^{-} \tag{5.18}$$

$$E(C)_{ox} + n \cdot e^{-} \rightarrow E(C)_{red} \tag{5.19}$$

The energy delivered to the external circuit as current and to the surrounding ambient as heat is the difference in the bonding energy between the commencement and the conclusion of the battery's reaction (see Eq. (5.20)).

$$\left(E(A)_{red} + E(C)_{ox}\right)_{sta} - \left(E(A)_{ox} + E(C)_{red}\right) = electricity + heat \tag{5.20}$$

During charging, the electrons move from the cathode to the anode through the external circuit. The positive ions move from the cathode to the anode through the electrolyte, and the negative ions move from the anode to the cathode also through the electrolyte (see Fig. 5.10).

The substances reacting are usually stored in the electrodes or in the electrolyte. This is the case in lead-acid batteries. The substances reacting are stored in separate tanks in flow batteries.

The electromotive force of a battery enables electrons to move, contingent on the difference between the electric potentials of the electrodes. The voltage to the terminals equals the difference between the electromotive force and the internal resistance. Then lower is the value of the internal resistance, then higher is the round-trip efficiency of the battery.

Lithium-ion batteries are some of the most widespread secondary battery technologies. The cathode is made of lithiated metal oxide ($LiCoO_2$), and the anode is layered graphitic carbon. The electrolyte consists of lithium salts dissolved in organic carbonate. During charging, the lithium in the $LiCoO_2$ is ionized, and the ions move to the cathode where they intercalate in the graphite layers (see Fig. 5.11). During discharging, the lithium ions move from the anode to the cathode where they intercalate in the crystal structure. Equations (5.21) and (5.22) present the main chemical reactions:

$$Cathode: LiCoO_2 \leftrightarrow Li_{1-x}CoO_2 + xLi^{+} + xe^{-} \tag{5.21}$$

$$Anode: xLi^{+} + xe^{-} + xC_6 \leftrightarrow xL_iC_6. \tag{5.22}$$

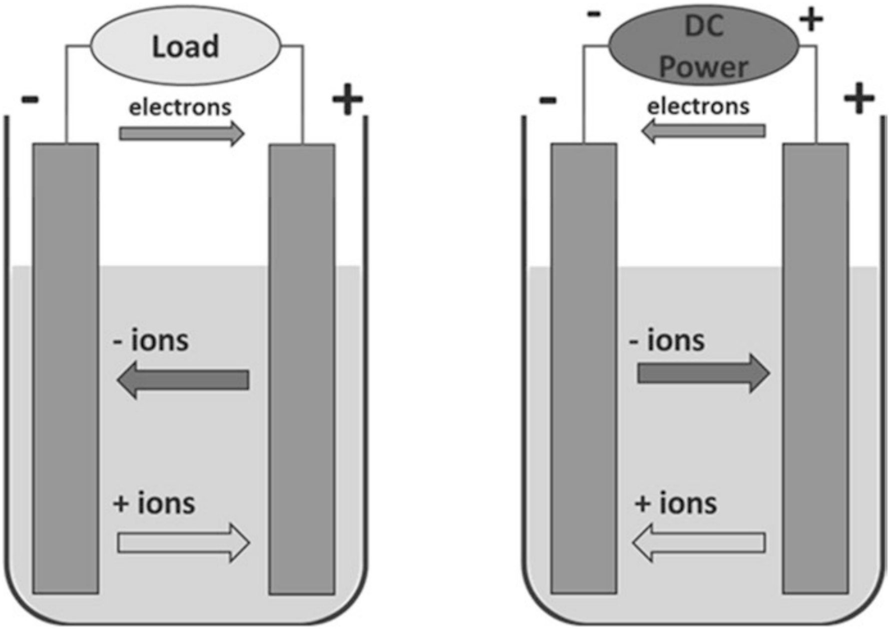


Fig. 5.10 Movement of electrons and ions during discharging (*left*) and charging (*right*)

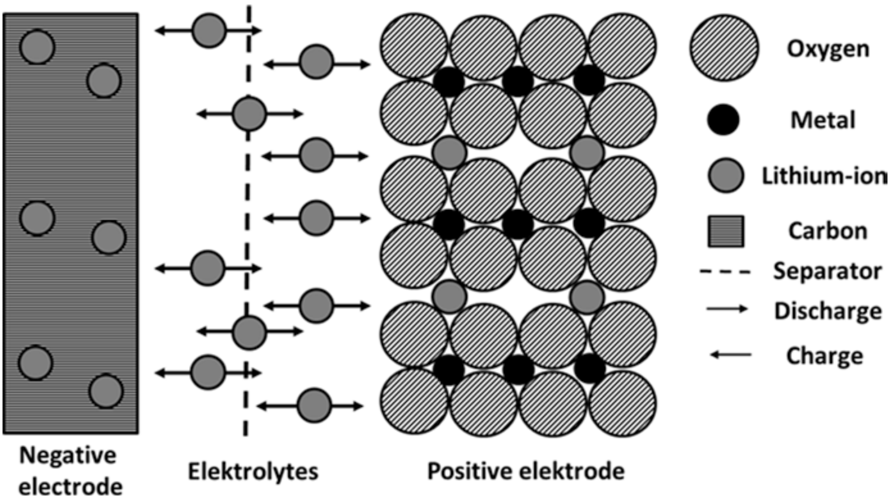


Fig. 5.11 Charging and discharging of a lithium-ion cell based on LiMeO2 cathode material and a carbon-based anode

Commercially available lithium-ion batteries have a round-trip efficiency of between 80 and 85 % and a life of 5000 full cycles. The specific energy density ranges between 100 and 250 W/kg, while the specific power density varies between 300 and 1500 W/kg. Round-trip efficiency is expected to reach 90 % and a life of 10,000 full cycles by 2030. An example of lithium-ion battery is depicted in Fig. 5.12.

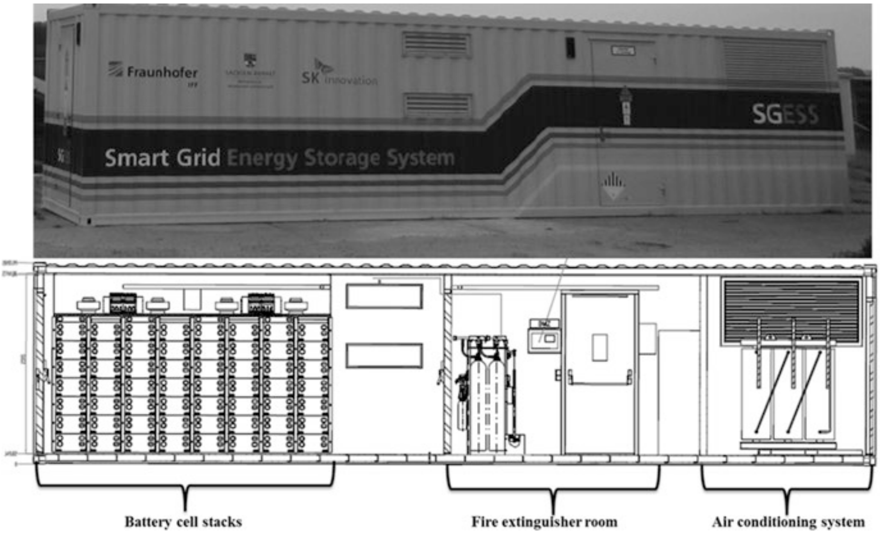


Fig. 5.12 Lithium-ion battery (1 MW, 500 kWh) in operation at Fraunhofer Institute IFF Magdeburg, Germany (*top*) and its layout (*bottom*)

Lithium-ion batteries can be used for power quality (frequency and voltage control), as well as energy-management applications (integration of volatile renewables). A variety of large lithium-ion batteries (up to different tens W and tens MWh) have been installed all over the world in recent years.

Research on lithium-ion batteries has concentrated primarily on testing new materials for electrodes and electrolytes that cut costs, improve efficiency, and increase life and safety.

In addition to lithium-ion batteries, more and more high-temperature batteries have been connected to the grid in recent years. Sodium-sulfur (NaS) batteries are used most frequently. To date, over 300 MW in NaS batteries have been installed worldwide. Unlike lithium-ion batteries, high-temperature batteries use a beta alumina solid material (β''-Al_{2O3}) as the electrolyte and have molten (sulfur and sodium) electrodes. Since these batteries have to have a temperature of 270–350 °C in order to keep the electrodes in a liquid state, they must be thermally insulated. They use an internal ohmic heater to maintain high temperatures during standby.

During the discharging phase, the sodium is oxidized and the sulfur is reduced to form sodium polysilfides Na_{2S_x} (x = 3–5) in the positive electrodes (see Eq. (5.23)). This reaction is highly exothermic, which contributes to keeping the temperature of the whole battery at a high level.

$$2Na + xS \leftrightarrow Na_2S_x \tag{5.23}$$

Only one company manufactures NaS batteries at the present time. The structure employed stores the sodium inside a tubular container made of a solid electrolyte surrounded by the sulfur (cathode) (see Fig. 5.13). Its round-trip efficiency ranges

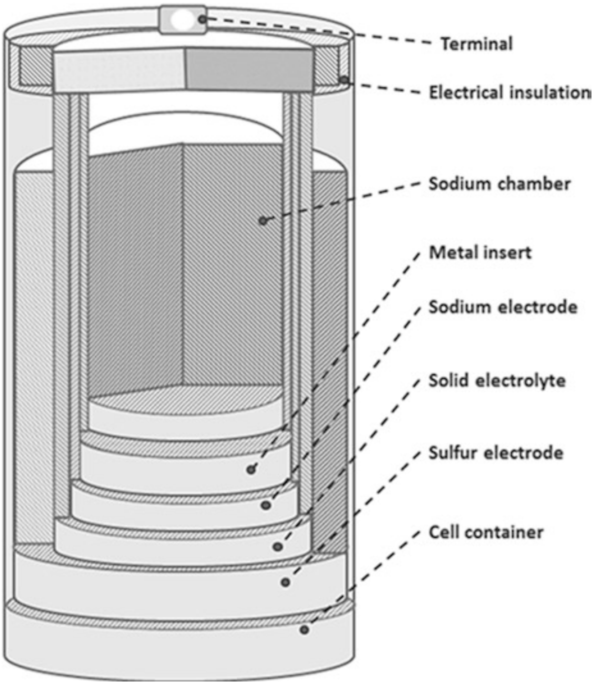


Fig. 5.13 A NaS battery

between 75 and 80 %, and its life can reach 10,000 full cycles. The energy and power density are in the range of 150–250 W/kg and 150–230 W/kg, respectively. High-temperature NaS batteries can be used for power quality and energy-management applications. Their pulse power capability is five times higher than the nominal value for 30 s (Fig. 5.14).

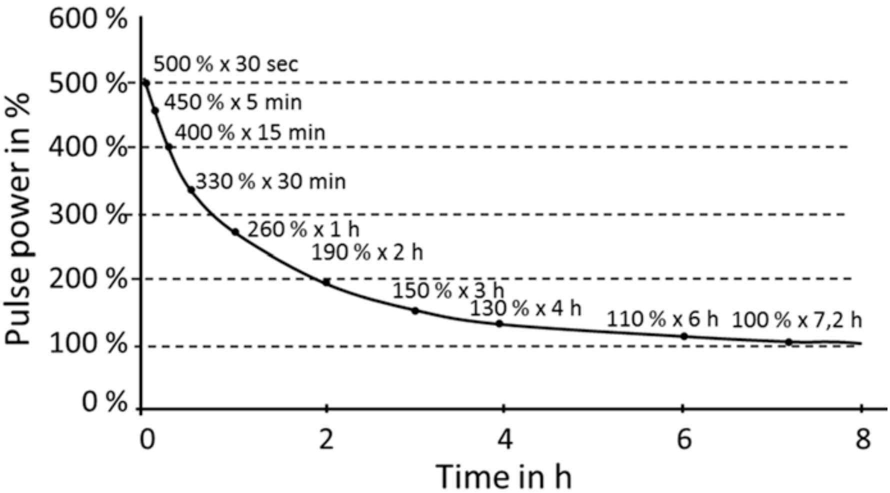


Fig. 5.14 Pulse factor of a high-temperature NaS battery

In addition to lithium-ion and sodium-sulfur batteries, lead-acid batteries are often used in power applications, mostly as backup systems. The electrodes in lead-acid batteries consist of lead and lead coated with lead dioxide (PbO_2) (see Fig. 5.15). The electrolyte is a dilute solution of sulfuric acid (H_2SO_4). During discharging, both electrodes are converted into lead sulfate ($PbSO_4$), consuming sulfuric acid from the electrolyte. During charging, the lead sulfate is converted into sulfuric acid, forming a layer of metallic lead in the anode (see Eq. (5.24)) and a layer of lead dioxide in the cathode (see Eq. (5.25)). During charging, the electrolyte's water is additionally split into hydrogen and oxygen and released into the atmosphere. This makes it necessary to add water to the system. This problem can be circumvented by adding silica to the electrolyte to form a gel.

$$P_bSO_4 + 2H_2 + 2e^- \leftrightarrow H_2SO_4 + P_b \quad (5.24)$$

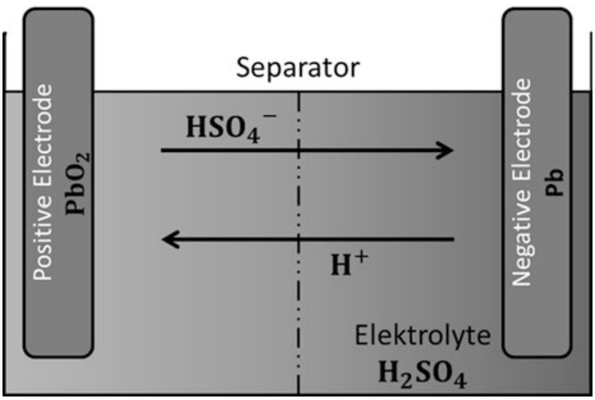
$$P_bSO_4 + 2H_2O \leftrightarrow P_bO_2 + H_2SO_4 + 2H_2 + 2e^- \quad (5.25)$$

Although the round/trip efficiency between 75 and 80 % is similar to other battery technologies, the life of a lead-acid battery is very limited and ranges between 500 and 2000 cycles. It depends mostly on the DoD. High DoD intensifies corrosion and electrode material shedding. Temperature also affects the storage capacity, e.g., storage capacity at –4 °C is 70–80% of what it is at 24 °C. Energy and power density, 33–42 W/kg and 180 W/kg, respectively, are also limited.

Unlike conventional batteries, flow batteries employ liquid electrolytes stored in two separate tanks. During charging and discharging, the electrolytes are pumped into the stack, which contains an ion-exchanger membrane or an electrode array. Energy is stored in the active materials dissolved in the electrolytes.

Vanadium is one of the active materials used most commonly in electrolytes. Vanadium redox couples (V^{2+}/V^{3+}) are pumped into the anode half-cell and the V^{4+}/V^{5+} in the cathode half-cell. Active materials are fully dissolved in sulfuric acid electrolyte solutions. During discharging, the V^{2+} in the anode half-cell is oxidized into V^{3+} and one electron is released to the external circuit (see Eq. (5.26)). At the

Fig. 5.15 A lead-acid cell



same time, the V^{5+} (in the form of VO_2^+) in the cathode half-cell accepts one electron from the external circuit and is reduced to V^{4+} (in the form of VO^{2+}) (see Eq. (5.27)).

$$V^{2+} \leftrightarrow V^{3+} + e^- \tag{5.26}$$

$$VO_2^+ + 2H^+ \leftrightarrow VO^{2+} + H_2O - e^- \tag{5.27}$$

Unlike conventional batteries, the energy capacity of flow batteries is limited only by the size of the tanks and the number of electrolytes. An additional benefit is avoiding the need to balance the cells, which is typical of multi-cell batteries. Flow batteries have a round-trip efficiency of 65–72 %. It is lower than the round-trip efficiency of other batteries because flow batteries have additional auxiliary loads, for example, electrolyte pumps. The life of flow batteries is only limited by the service life of the two pumps and the membrane, which should be replaced about every 10,000 cycles. The energy density ranges between 10 and 20 W/kg, lower than that of lead-acid batteries.

5.7 Superconducting Magnetic Energy Storage

The SMES stores the electricity in form of a magnetic field created by the flow of direct current (DC) in a superconducting coil. Different from the other energy storage technologies, the only conversion process presented in the SMES is the conversion from the alternating current (AC) to DC. As a consequence, the associated

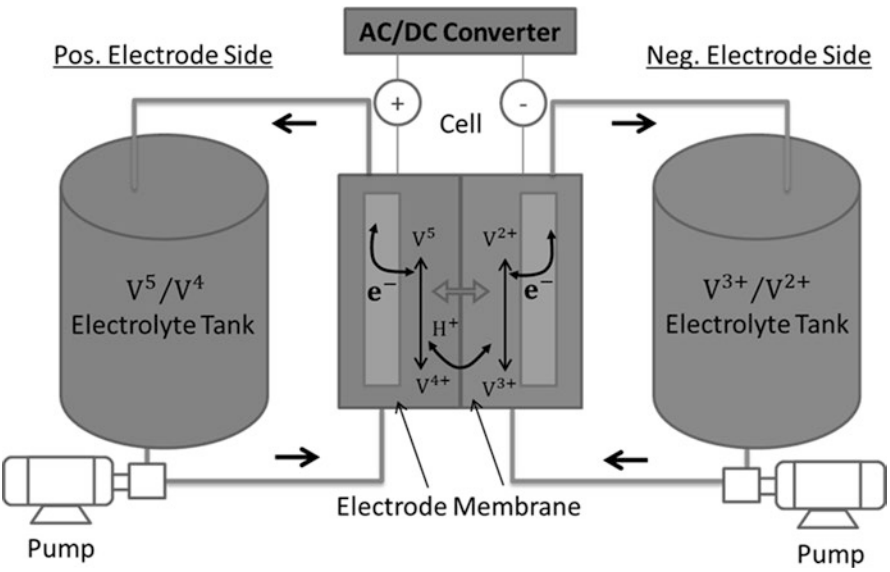


Fig. 5.16 A vanadium-redox flow battery

losses are very low and the storage efficiency very high (about 95 %). Even if SMES systems are capable of storing large amounts of energy and, therefore, could be used for energy applications such as load leveling, thanks to their rapid discharge capability, they are mostly used for power applications such as system stability.

The SMES systems are composed of four main components: a superconducting coil, a refrigerator, a power conversion system (PCS) and a control system (see Fig. 5.17). The energy is stored in the superconducting coil in the form of a magnetic field generated by the flow of DC. As indicated in Eq. (5.28), the stored energy (E) is linearly proportional to the inductance of the coil (L) and squarely proportional to the circulating current (I). The storage capacity is determined by the size and the geometry of the coil, while the storage power is determined by the characteristics of the superconductor, which, in turn, determines the maximum current. The superconductor is typically made from an alloy of niobium and titanium (Nb-Ti) (see Fig. 5.18), which operates at about 4.2 °K (–269 °C). At this temperature, the resistance is typically zero. A cryogenic refrigerator is needed in order to reach this temperature. It is composed of various compressors and a vacuum enclosure. Helium is used as the cooling medium because it is the only material which is not a solid at that temperature. The compressed helium in the vacuum enclosure changes its phase in the liquid one, which is used for cooling the coil. The PCS works as an interface between the power grid (AC) and the superconducting coil (DC). The control system manages the SMES according to the signals received from the grid and the status of the SMES.

$$E = \frac{1}{2} L I^2 \tag{5.28}$$

The energy storage capacity for SMES systems ranges from a few MJs to hundreds of MJs. A SMES system is able to discharge its total energy in a second.

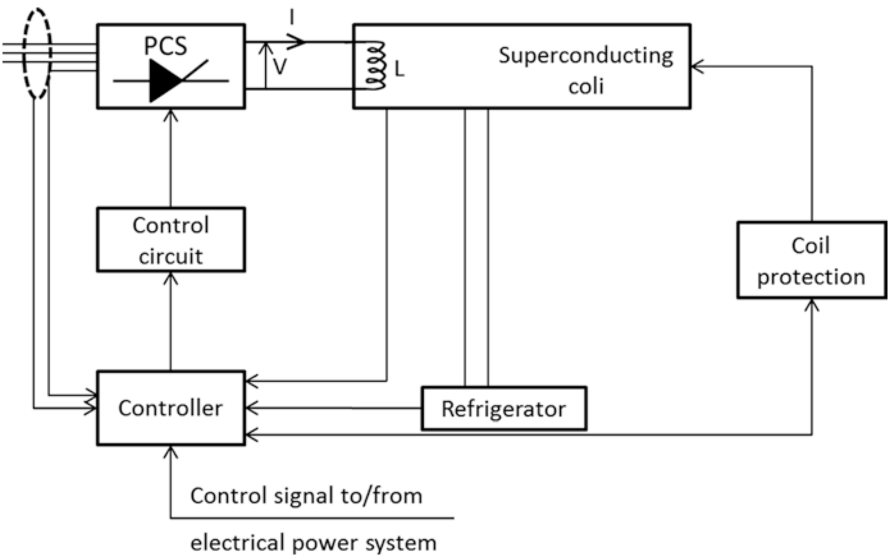


Fig. 5.17 Scheme of a SMES system

Fig. 5.18 Superconducting wire (www.luvata.com)

5.8 Power-to-Gas

The term “power-to-gas” generally refers to two different methods of electricity storage. In the first, electricity is converted and stored as hydrogen. In the second, electricity is converted into hydrogen and, subsequently, this hydrogen is methanated and stored as methane. Both processes require an electrolyzer system that uses electricity to convert deionized water into hydrogen and oxygen (see Eq. (5.29)):

$$2H_2O \leftrightarrow 2H_2 + O_2. \tag{5.29}$$

Part of the electricity used to split the water into hydrogen and oxygen is lost in the electrolyzer as heat. Other parts are lost in the rectifier and in auxiliary equipment, e.g., the compressor. All of these effects decrease the electrolyzer system’s efficiency, which is generally referred to as the higher heating value (HHV) of the gas. (Hydrogen’s HHV is 39.44 kW/kg.) Two different types of industrial electrolyzers are normally used: alkaline and proton-exchange membrane (PEM) electrolyzers. The overall efficiency of these systems ranges from 56 to 73 %, depending on the type of electrolyzer (the PEM electrolyzer has the lowest efficiency value).

The methanation process is based on combining four moles of hydrogen to one mole of carbon dioxide (CO_2) to obtain one mole of methane and two moles of steam (see Eq. (5.30)). Also known as the Sabatier reaction, this exothermic process (0.045 kW/mol) requires high temperature and high pressure to produce a large amount of methane. The efficiency of the reaction ranges from 75 to 80 %.

$$4H_2 + CO_2 \leftrightarrow CH_4 + 2H_2O \tag{5.30}$$

The overall efficiency of the power-to-gas process (with methanation) ranges from 42 to 58 %. This value does not factor in the transformation of the gas into electricity. When

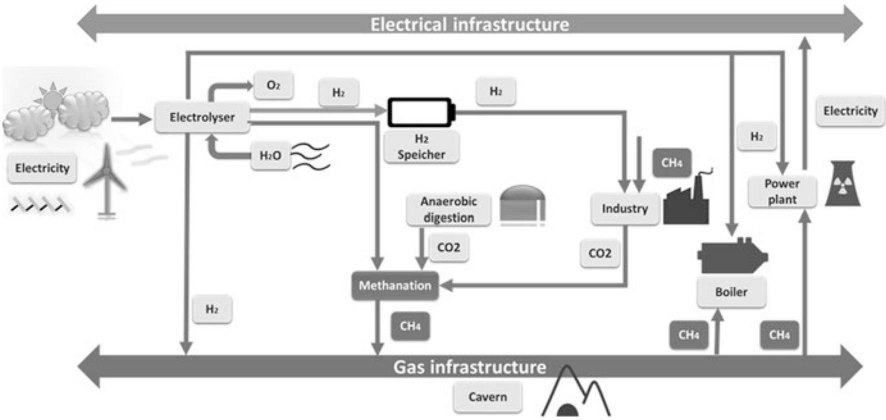


Fig. 5.19 Power-to-gas scheme [6]

the stored methane is burned in a combined-cycle power plant with an electric efficiency of 60 %, then the overall efficiency of the power-to-gas process (from electricity to electricity) is about 30 %. The efficiency of the power-to-gas process can be increased by recovering the heat generated when the water is split. One potential application for this is fermentation in biogas plants. Since biogas plants need heat for fermentation and emit free CO_2 to the atmosphere, which can be reused to make methanate hydrogen, biogas can be viewed as complementary to the power-to-gas systems because it is a CO_2 neutral emission. Figure 5.19 depicts an example of a power-to-gas concept. The electrolyzers convert the surplus electricity generated by RES into hydrogen. The methanizers combine the hydrogen with the CO_2 emitted by biogas plants. The methane produced is then fed into the natural-gas network. The gas is used to generate either electricity (e.g., in gas–turbine power plants) or thermal power for heating or industrial purposes.

In contrast to the power-to-gas system's lower energy efficiency compared to other energy storage systems, its chief advantages are environmental and economic. A power-to-gas system burns hydrogen or methane in a carbon-free process when the gas is produced from renewable-energy sources. The primary economic advantage is the elimination of notable capital expenditure by utilizing the existing natural-gas infrastructure (e.g., pipelines, compressors, caverns). Over 200,000 km of natural-gas transmission pipelines and more than 200 caverns are in operation in Europe (see Fig. 5.20) They transmitted 5,058,000 GWh of energy in 2011. The American natural-gas system, considerably larger than the European natural-gas system, has some 490,000 km of high-pressure pipelines, 1400 compressors and 400 caverns (see Fig. 5.21). However, power to gas also has some limitations. Complications can occur in power-to-gas systems that store electricity as hydrogen when the latter is fed into the natural-gas network. The reasons are the components that typically make up the natural-gas network structure, such as pipelines, compressors, caverns, gas turbines and instrumentation. Originating from the potential problems caused by reactions between the materials, the greatest limitation is due to composing the pipeline medium. Opinions on the volume of hydrogen that natural-gas pipelines are able to transport vary in the literature and range between 10 and 50 %.

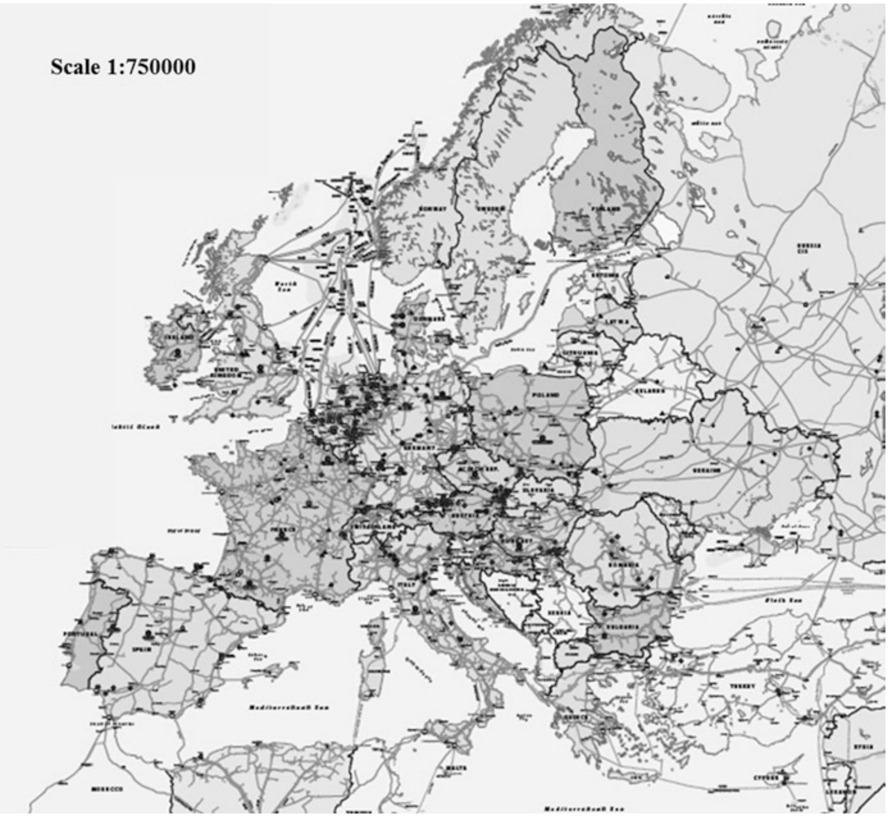


Fig. 5.20 The European natural-gas pipeline in 2014 [7]

Centrifugal compressors with a compression ratio of around 15 bars are normally used. They are driven by open-cycle gas turbines that burn natural gas taken from the natural- gas pipeline and require approximately 20–25 MW of power to drive the compressor. Compressor blade materials, the amount of energy required to compress the hydrogen-methane mixture and the boiler of the gas turbine impose limitations on compressors. The materials employed should enable the compressors actually used in the natural-gas network to compress a volume of up to 5 % hydrogen without any problem. The energy to compress the gas is calculated by Eq. (5.31), where γ is the ratio of the specific heat, p is the pressure, V is the volumetric density and the subscripts 0 and 1 indicate the initial and final compression.

$$W = \frac{\gamma}{\gamma - 1} p_0 V_0 \left[\left(\frac{p_1}{p_0} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \tag{5.31}$$

By considering the same compression ratio and the same mass flow rate, the energy to compress the hydrogen-methane mixture grows by increasing the volumetric percentage of hydrogen (Fig. 5.22). Approximately nine times as much energy

Fig. 5.21 The US network of natural-gas pipelines in 2009 [8]

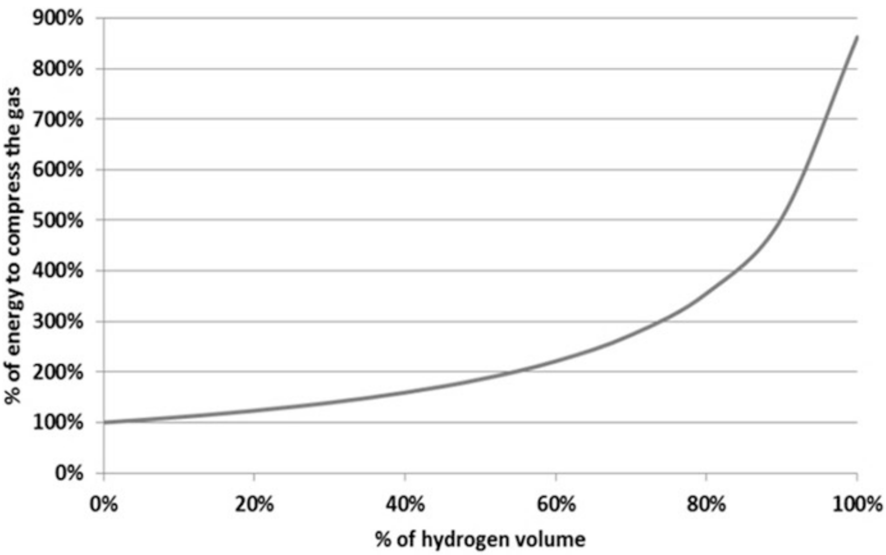


Fig. 5.22 The energy required to compress a hydrogen-methane mixture compared to the energy required to compress methane alone

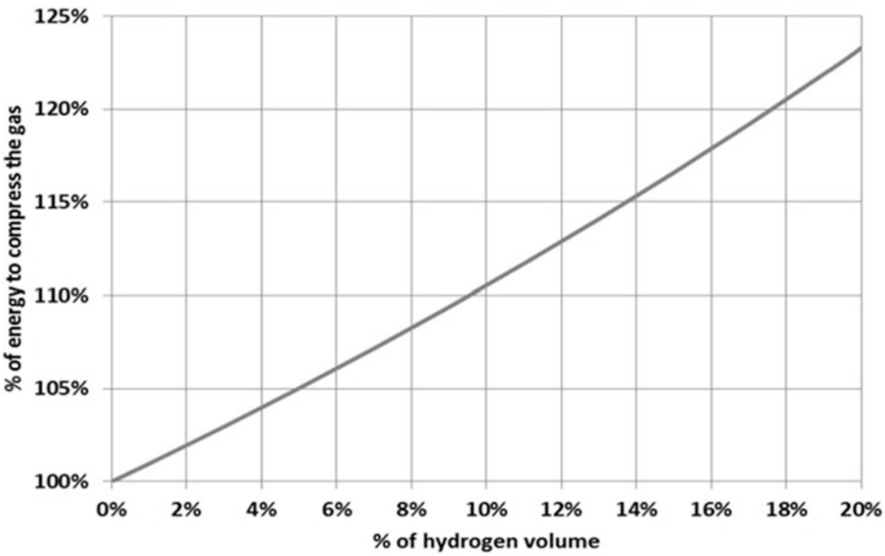


Fig. 5.23 The energy required to compress a hydrogen-methane mixture compared to the energy required to compress methane alone

is required to compress hydrogen alone than to compress methane alone. When the concentration of hydrogen is 10–15 % by volume, the power required to compress the mixture increases 10–17 % (Fig. 5.23). Since compressors are generally designed for (approximately 10–15 %) more power than nominal power, a mixture with as much as 14 % hydrogen-methane can be fed into the natural-gas network.

Gas-turbine boilers have different limitations. The main problems of burning a hydrogen-methane mixture are caused by the various burning velocities of the mixture (Table 5.4), which can destabilize the burning process and damage the boiler. Commercial gas turbines can burn a hydrogen-methane mixture of 0–8.5 % hydrogen. Some tests have demonstrated that boilers can be modified to burn a volume of up to 60 % hydrogen.

Table 5.4 Burning velocity of hydrogen and methane [5]

	Hydrogen	Methane
Burning velocity [cm/s]	306	33.8

Table 5.5 Maximum limits of hydrogen in a natural-gas network

Natural gas network components	Maximum limits [% of H_2 by volume]
Transport pipeline	50 %
Compressors	14 %
Caverns	55 %
Instrumentation	30 %
Gas turbine	1–3 %

Fewer limitations arise from the usage of the caverns. The experience of the past years about so-called town gas has shown that up to 55 % hydrogen by volume could be stored inside caverns. With reference to the measurement devices, different studies have shown that the devices actually used in the natural-gas network are able to work without any particular problem up to 10–30 %. Table 5.5 provides an overview of the maximum limits of hydrogen in a natural-gas network.

5.9 Compressed-Air Energy Storage

A CAES system can store electricity as mechanical energy alone (in a diabatic system) or as mechanical and thermal energy (in an adiabatic system). In both cases, the electricity is used to drive a compressor train that compresses and stores air in an underground space, such as an unlined cavern, and porous strata or a lined cavern and salt formation (see Fig. 5.24). During the discharge phase, the compressed air is heated before it expands in the turbine. The compressed air can be heated in burners (in a diabatic CAES) or in a thermal exchanger system (in an adiabatic CAES), which reuses the thermal energy recovered during compression. The CAES systems that are the most thermodynamically efficient continuously subtract heat during compression and continuously add heat during expansion, keeping the air at its ambient value, but, although the use of hydraulic air or water injection have been proposed, such isothermal processes are not easily achieved in practice. Since most compressors and turbines exchange a limited amount of heat with the atmosphere, their processes can be regarded as adiabatic. In reality, isothermal compression is replaced by sequences of adiabatic compressions with intermediate cooling, while isothermal expansion is replaced by adiabatic expansion with intermediate heating.

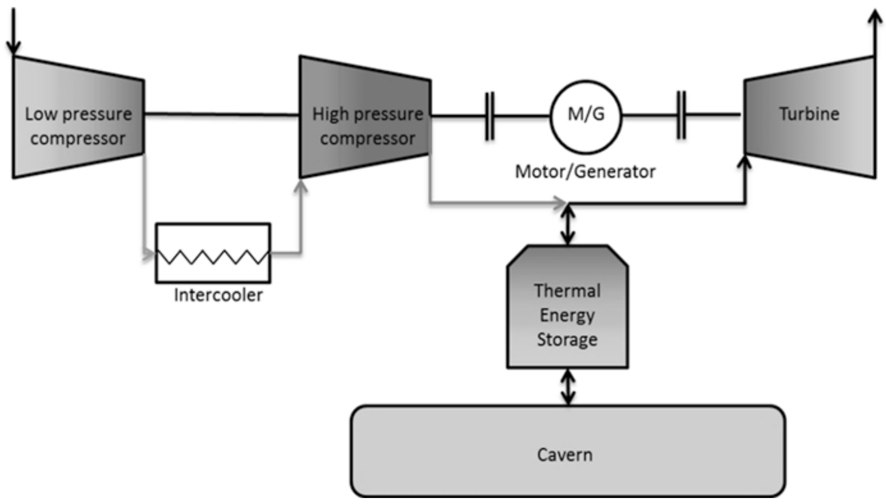


Fig. 5.24 Adiabatic compressed-air energy storage scheme [9]

Diabatic CAES systems are a hybrid of an energy storage system and a gas-turbine plant. Unlike conventional gas turbines, CAES systems precompress air in appropriate underground spaces and utilize it later by burning it in a burner together with a gaseous fuel, such as natural gas. In order to increase the overall efficiency, a recuperator may be used to preheat compressed air before it enters the combustion chamber. A recuperator recovers part of the energy from exhaust gases, thus reducing the need to burn fuel. The overall efficiency of diabatic CAES plants ranges between 54 and 42 %, depending on their configuration, i.e., whether or not they have a recuperator. There are currently two diabatic CAES plants in operation worldwide.

The heat generated during the compression of air (charging phase) in an adiabatic CAES system (A-CAES) is stored in a thermal-energy storage (TES) system. In some design projects, such as the ADELE project, the compressor train compresses air to as much as 50–70 bar. The compressed air heated to over 600–650 °C flows into the TES system. The heat-storage material inside the TES is then heated as the temperature of the compressed air drops. The cooled compressed air is conducted into an underground cavern at about 50 °C. During the discharge phase, the compressed air flows over the TES material once again, thus, raising its temperature. The heated compressed air flows inside the turbine which drives an electric generator. The round-trip efficiency is expected to reach a value of approximately 60–70 %.

The application domain of adiabatic CAES systems ranges from energy management to electrical-grid support. In the latter case, apart from local system services, such as short-circuit power and reactive power provision, A-CAES systems can, in principle, deliver primary, secondary and tertiary (minute reserve) controls. However, A-CAES systems can only supply these services for primary and secondary control under certain operational conditions, as is typical for any kind of thermal-power plant due to the material-related thermal-stress restrictions of the turbo machinery.

Test Questions Chap. 5

- What kinds of flexibility options in the power system can be replaced by energy storage?
- What are the main criteria used to classify energy-storage systems?
- What are the main components that limit the lifetime of redox-flow batteries?
- What is the maximal amount of hydrogen that should be fed into the natural gas network and why?
- List the differences between diabatic compressed-air storage systems and the adiabatic version.

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