Unit-II

TYPES OF ELECTRICAL ENERGY STORAGE SYSTEMS

Electrical storage systems, Double-layer capacitors (DLC), Superconducting magnetic energy storage (SMES), super charging stations, Thermal storage systems, Standards for EES, Technical comparison of EES technologies.

Introduction

In this section the types of EES system and their features are listed. A brief classification is followed by a description of the various EES types with their advantages and disadvantages. Finally the main technical features are summarized.

2.1 Classification of EES systems

A widely-used approach for classifying EES systems is the determination according to the form of energy used. In Figure 2-1 EES systems are classified into mechanical, electrochemical, chemical, electrical and thermal energy storage systems. Hydrogen and synthetic natural gas (SNG) are secondary energy carriers and can be used to store electrical energy via electrolysis of water to produce hydrogen and, in an additional step, methane if required. In fuel cells electricity is generated by oxidizing hydrogen or methane. This combined electrolysis-fuel cell process is an electrochemical EES. However, both gases are multi-purpose energy carriers. For example, electricity can be generated in a gas or steam turbine. Consequently, they are classified as chemical energy storage systems. In Figure 2-1 thermal energy storage systems are included as well, although in most cases electricity is not the direct input to such storage systems. But with the help of thermal energy storage the energy from renewable energy sources can be buffered and thus electricity can be produced on demand. Examples are hot molten salts in concentrated solar power plants and the storage of heat in compressed air plants using an adiabatic process to gain efficiency.

2.2 Mechanical storage systems

The most common mechanical storage systems are pumped hydroelectric power plants (pumped hydro storage, PHS), compressed air energy storage (CAES) and flywheel energy storage (FES).

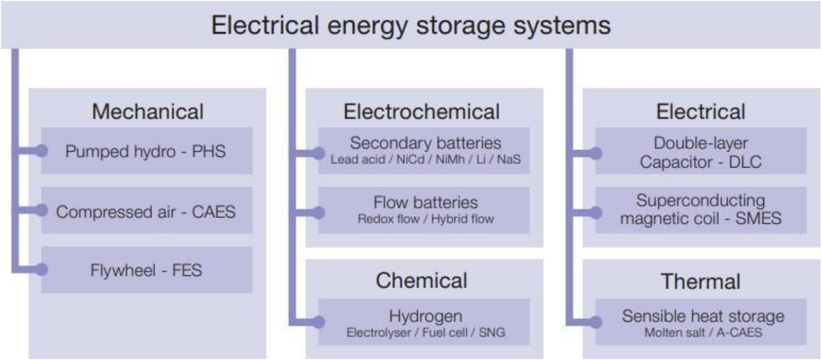


Figure.2.1 Classification of electrical energy storage systems according to energy form

2.2.1Pumped hydro storage (PHS)

With over 120 GW, pumped hydro storage power plants (Figure 2-2) represent nearly 99 % of world-wide installed electrical storage capacity [doe07], which is about 3 % of global generation capacity 4 . Conventional pumped hydro storage systems use two water reservoirs at different elevations to pump water during off-peak hours from the lower to the upper reservoir (charging). When required, the water flows back from the upper to the lower reservoir, powering a turbine with a generator to produce electricity (discharging). There are different options for the upper and lower reservoirs, e.g. high dams can be used as pumped hydro storage plants. For the lower reservoir flooded mine shafts, other underground cavities and the open sea are also technically possible. Seawater pumped hydro plant was first built in Japan in 1999 (Yanbaru, 30 MW). PHS has existed for a long time – the first pumped hydro storage plants were used in Italy and Switzerland in the 1890s. By 1933 reversible pump-turbines with motor generators were available 5. Typical discharge times range from several hours to a few days. The efficiency of PHS plants is in the range of 70 % to 85 %. Advantages are the very long lifetime and practically unlimited cycle stability of the installation. Main drawbacks are the dependence on topographical conditions and large land use. The main applications are for energy management via time shift, namely non spinning reserve and supply reserve.

Figure.2.2 Pumped Hydro Storage

2.2.2 Compressed air energy storage (CAES)

Compressed air (compressed gas) energy storage (Figure 4.3) is a technology known and used since the 19th century for different industrial applications including mobile ones. Air is used as storage medium due to its availability. Electricity is used to compress air and store it in either an underground structure or an above-ground system of vessels or pipes. When needed the compressed air is mixed with natural gas, burned and expanded in a modified gas turbine. Typical underground storage options are caverns, aquifers or abandoned mines. If the heat released during compression is dissipated by cooling and not stored, the air must be reheated prior to expansion in the turbine. This process is called diabatic CAES and results in low round-trip efficiencies of less than 50 %. Diabatic technology is well proven; the plants have a high reliability and are capable of starting without extraneous power 6. The advantage of CAES is its large capacity; disadvantages are low round-trip efficiency and geographic limitation of locations [nak07].

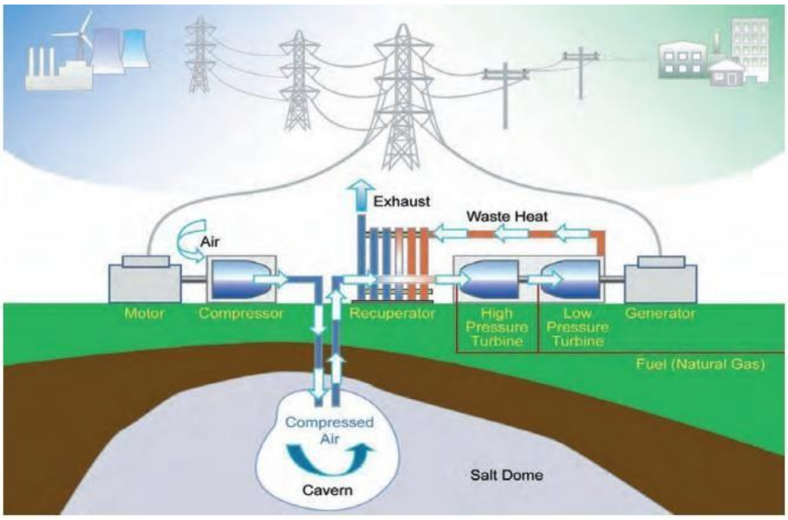


Figure.4.3 Underground CAES

2.2.3 Flywheel energy storage (FES)

In flywheel energy storage (Figure 4.4) rotational energy is stored in an accelerated rotor, a massive rotating cylinder. The main components of a flywheel are the rotating body/cylinder (comprised of a rim attached to a shaft) in a compartment, the bearings and the transmission device (motor/generator mounted onto the stator 7). The energy is maintained in the flywheel by keeping the rotating body at a constant speed. An increase in the speed results in a higher amount of energy stored. To accelerate the flywheel electricity is supplied by a transmission device. If the flywheel's rotational speed is reduced electricity may be extracted from the system by the same transmission device. Flywheels of the first generation, which have been available since about 1970, use a large steel rotating body on mechanical bearings. Advanced FES systems have rotors made of high-strength carbon filaments, suspended by magnetic bearings, and spinning at speeds from 20 000 to over 50 000 rpm in a vacuum enclosure. The main features of flywheels are the excellent cycle stability and a long life, little maintenance, high power density and the use of environmentally inert material. However, flywheels have a high level of self- discharge due to air resistance and bearing losses and suffer from low current efficiency. Today flywheels are commercially deployed for power quality in industrial and UPS applications, mainly in a hybrid configuration. Efforts are being made to optimize flywheels for long-duration operation (up to several hours) as power storage devices for use in vehicles and power plants.

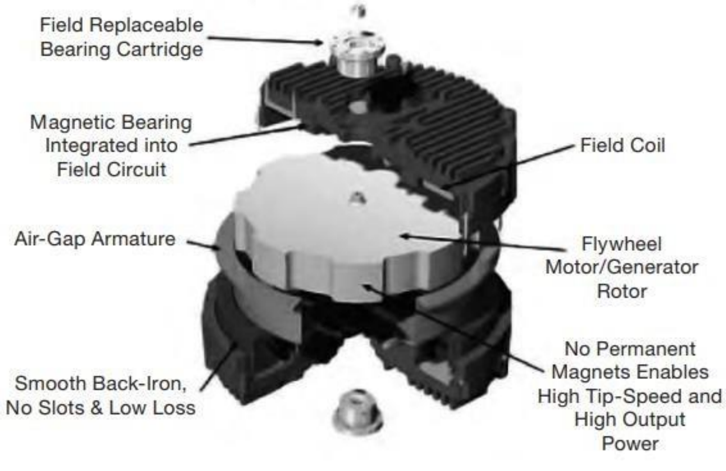


Figure.4.5 Flywheel energy storage

2.3Electrochemical storage systems

In this section various types of batteries are described. Most of them are technologically mature for practical use. First, six secondary battery types are listed: lead acid, NiCd/NiMH, Li-ion, metal air, sodium sulphur and sodium nickel chloride; then follow two sorts of flow battery.

2.3.1Secondary batteries

Lead acid battery (LA)

Lead acid batteries are the worlds most widely used battery type and have been commercially deployed since about 1890. Lead acid battery systems are used in both mobile and stationary applications. Their typical applications are emergency power supply systems, stand-alone systems with PV, battery systems for mitigation of output fluctuations from wind power and as starter batteries in vehicles. In the past, early in the “electrification age” (1910 to 1945), many lead acid batteries were used for storage in grids. Stationary lead acid batteries have to meet far higher product quality standards than starter batteries. Typical service life is 6 to 15 years with a cycle life of 1 500 cycles at 80 % depth of discharge, and they achieve cycle efficiency levels of around 80 % to 90 %. Lead acid batteries offer a mature and well-researched technology at low cost. There are many types of lead acid batteries available, e.g. vented and sealed housing versions (called valve-regulated lead acid batteries, VRLA). Costs for stationary batteries are currently far higher than for starter batteries. Mass production of lead acid batteries for stationary systems may lead to a price reduction. One disadvantage of lead acid batteries is usable capacity decrease when high power is discharged. For example, if a battery is discharged in one hour, only about 50 % to 70 % of the rated capacity is available. Other drawbacks are lower energy density and the use of lead, a hazardous material prohibited or restricted in various jurisdictions. Advantages are a favorable cost/performance ratio, easy recyclability and a simple charging technology. Current R&D on lead acid batteries is trying to improve their behavior for micro-hybrid electric vehicles.

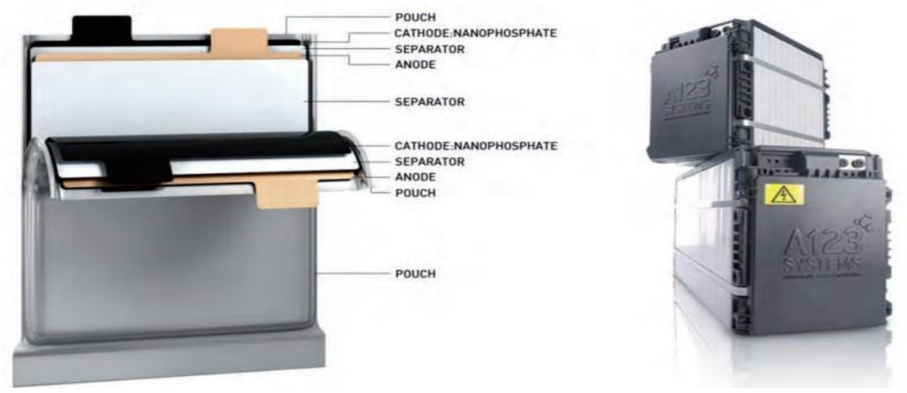
Nickel cadmium and nickel metal hydride battery (NiCd, NiMH)

Before the commercial introduction of nickel metal hydride (NiMH) batteries around 1995, nickel cadmium (NiCd) batteries had been in commercial use since about 1915. Compared to lead acid batteries, nickel-based batteries have a higher power density, a slightly greater energy density and the number of cycles is higher; many sealed construction types are available. From a technical point of view, NiCd batteries are a very successful battery product; in particular, these are the only batteries capable of performing well even at low temperatures in the range from -20 °C to -40 °C. Large battery systems using vented NiCd batteries operate on a scale similar to lead acid batteries. However, because of the toxicity of cadmium, these batteries are presently used only for stationary applications in Europe. Since 2006 they have been prohibited for consumer use. NiMH batteries were developed initially to replace NiCd batteries. Indeed, NiMH batteries have all the positive properties of NiCd batteries, with the exception of the maximal nominal capacity which is still ten times less when compared to NiCd and lead acid. Furthermore, NiMH batteries have much higher energy densities (weight for weight). In portable and mobile applications sealed NiMH batteries have been extensively replaced by lithium ion batteries. On the other hand, hybrid vehicles available on today’s market operate almost exclusively with sealed NiMH batteries, as these are robust and far safer than lithium ion batteries. NiMH batteries currently cost about the same as lithium ion batteries.

Lithium ion battery (Li-ion)

Lithium ion batteries (Figure 2-5) have become the most important storage technology in the areas of portable and mobile applications (e.g. laptop, cell phone, electric bicycle, and electric car) since around 2000. High cell voltage levels of up to 3.7 nominal Volts mean that the number of cells in series with the associated connections and electronics can be reduced to obtain the target voltage. For example, one lithium ion cell can replace three NiCd or NiMH cells which have a cell voltage of only 1.2 Volts. Another advantage of Li-ion batteries is their high gravimetric energy density, and the prospect of large cost reductions through mass production. Although Li-ion batteries have a share of over 50 % in the small portable devices market, there are still some challenges for developing larger-scale Li-ion batteries. The main obstacle is the high cost of more than USD 600/kWh due to special packaging and internal overcharge protection circuits. Lithium ion batteries generally have a very high efficiency, typically in the range of 95 % - 98 %. Nearly any discharge time from seconds to weeks can be realized, which makes them a very flexible and universal storage technology.

Standard cells with 5000 full cycles can be obtained on the market at short notice, but even higher cycle rates are possible after further development, mainly depending on the materials used for the electrodes. Since lithium ion batteries are currently still expensive, they can only compete with lead acid batteries in those applications which require short discharge times (e.g. as primary control backup). Safety is a serious issue in lithium ion battery technology. Most of the metal oxide electrodes are thermally unstable and can decompose at elevated temperatures, releasing oxygen which can lead to a thermal runaway. To minimize this risk, lithium ion batteries are equipped with a monitoring unit to avoid over- charging and over-discharging. Usually a voltage balance circuit is also installed to monitor the voltage level of each individual cell and prevent voltage deviations among them. Lithium ion battery technology is still developing, and there is considerable potential for further progress. Research is focused on the development of cathode materials.



Typical Li-ion prismatic cell design and battery modules

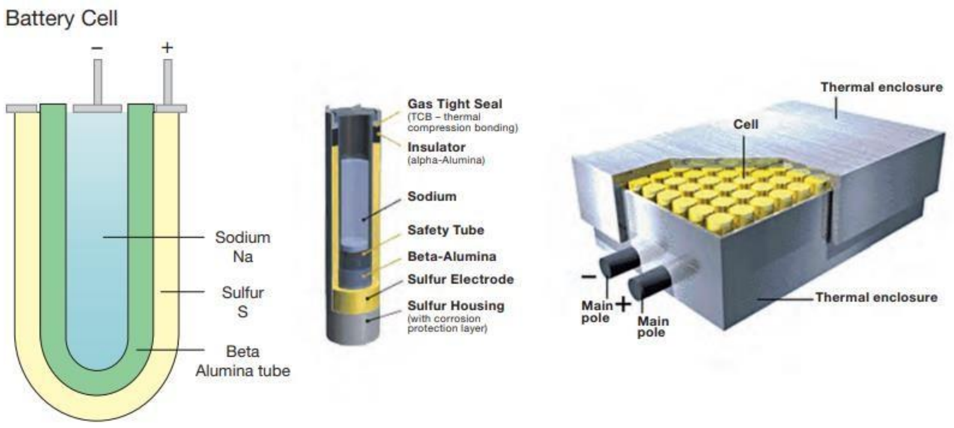
Metal air battery (Me-air)

A metal air electrochemical cell consists of the anode made from pure metal and the cathode connected to an inexhaustible supply of air. For the electrochemical reaction only the oxygen in the air is used. Among the various metal air battery chemical couples, the lithium air battery is most attractive since its theoretical specific energy excluding oxygen (oxygen is not stored in the battery) is 11.14 kWh/kg, corresponding to about 100 times more than other battery types and even greater than petrol (10.15 kWh/kg). However, the high reactivity of lithium with air and humidity can cause fire, which is a high safety risk. Currently only a zinc air battery with a theoretical specific energy excluding oxygen of 1.35 kWh/kg is technically feasible. Zinc air batteries have some properties of fuel cells and conventional batteries: the zinc is the fuel, the reaction rate can be controlled by varying air flow, and oxidized zinc/electrolyte paste can be replaced with fresh paste. In the 1970s, the development of thin electrodes based on fuel-cell research made small button prismatic primary cells possible for hearing aids, pagers and medical devices, especially cardiac telemetry. Rechargeable zinc air cells have a difficulty in design since zinc precipitation from the water based electrolyte must be closely controlled. A satisfactory, electrically rechargeable metal air system potentially offers low materials cost and high specific energy, but none has reached marketability yet.

Sodium sulphur battery (NaS)

Sodium sulphur batteries (Figure 2-6) consist of liquid (molten) sulphur at the positive electrode and liquid (molten) sodium at the negative electrode; the active materials are separated by a solid beta alumina ceramic electrolyte. The battery temperature is kept between 300 °C and 350 °C to keep the electrodes molten. NaS batteries reach typical life cycles of around 4 500 cycles and have a discharge time of 6.0 hours to 7.2 hours. They are efficient (AC-based round-trip efficiency is about 75 %) and have fast response. These attributes enable NaS batteries to be economically used in combined power quality and time shift applications with high energy density.

The NaS battery technology has been demonstrated at around 200 sites in Japan, mainly for peak shaving, and Germany, France, USA and UAE also have NaS batteries in operation. The main drawback is that to maintain operating temperatures a heat source is required, which uses the battery's own stored energy, partially reducing the battery performance. In daily use the temperature of the battery can almost be maintained by just its own reaction heat, with appropriately dimensioned insulation. Since around 1990 NaS batteries have been manufactured by one company in Japan, with a minimum module size of 50 kW and with typically 300 kWh to 360 kWh. It is not practical for the present to use only one isolated module. Because 20 modules are combined into one battery the minimal commercial power and energy range is on the order of 1 MW, and 6.0 MWh to 7.2 MWh. These batteries are suitable for applications with daily cycling. As the response time is in the range of milliseconds and NaS batteries meet the requirements for grid stabilization, this technology could be very interesting for utilities and large consumers.



NaS Battery: Cell design and 50 kW module

Sodium nickel chloride battery (NaNiCl)

The sodium nickel chloride (NaNiCl) battery, better known as the ZEBRA (Zero Emission Battery Research) battery, is – like the NaS battery – a high-temperature (HT) battery, and has been commercially available since about 1995. Its operating temperature is around 270 °C, and it uses nickel chloride instead of sulphur for the positive electrode. NaNiCl batteries can withstand limited overcharge and discharge and have potentially better safety characteristics and a higher cell voltage than NaS batteries. They tend to develop low resistance when faults occur and this is why cell faults in serial connections only result in the loss of the voltage from one cell, instead of premature failure of the complete system. These batteries have been successfully implemented in several electric vehicle designs (Think City, Smart EV) and are an interesting opportunity for fleet applications. Present research is in developing advanced versions of the ZEBRA battery with higher power densities for hybrid electric vehicles, and also high-energy versions for storing renewable energy for load-leveling and industrial applications [esp11].

2.3.2Flow batteries

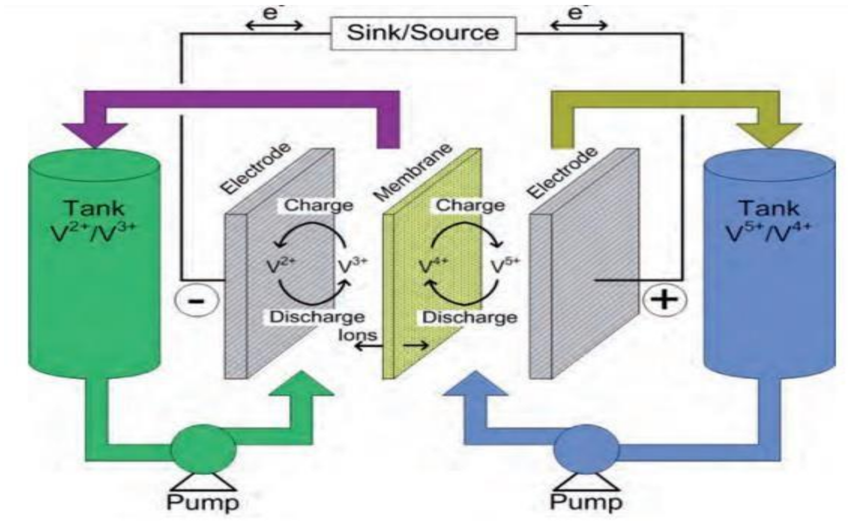
In conventional secondary batteries, the energy is charged and discharged in the active masses of the electrodes. A flow battery is also a rechargeable battery, but the energy is stored in one or more electro active species which are dissolved in liquid electrolytes. The electrolytes are stored externally in tanks and pumped through the electrochemical cell that converts chemical energy directly to electricity and vice versa. The power is defined by the size and design of the electrochemical cell whereas the energy depends on the size of the tanks. With this characteristic flow batteries can be fitted to a wide range of stationary applications. Originally developed by NASA in the early 70s as EES for long-term space flights, flow batteries are now receiving attention for storing energy for durations of hours or days with a power of up to several MW.

Flow batteries are classified into redox flow batteries and hybrid flow batteries.

Redox flow battery (RFB)

In redox flow batteries (RFB) two liquid electrolyte dissolutions containing dissolved metal ions as active masses are pumped to the opposite sides of the electrochemical cell. The electrolytes at the negative and positive electrodes are called anolyte and catholyte respectively. During charging and discharging the metal ions stay dissolved in the fluid electrolyte as liquid; no phase change of these active masses takes place. Anolyte and catholyte flow through porous electrodes, separated by a membrane which allows protons to pass through it for the electron transfer process. During the exchange of charge a current flows over the electrodes, which can be used by a battery-powered device. During discharge the electrodes are continually supplied with the dissolved active masses from the tanks; once they are converted the resulting product is removed to the tank. Theoretically a RFB can be “recharged” within a few minutes by pumping out the discharged electrolyte and replacing it with recharged electrolyte. That is why redox flow batteries are under discussion for mobile applications.

However, up to now the energy density of the electrolytes has been too low for electric vehicles. Today various redox couples have been investigated and tested in RFBs, such as a Fe-Ti system, a Fe-Cr system and a polyS-Br system (Rareness installation in UK with 15 MW and 120 MWh, but never commissioned). The vanadium redox flow battery (VRFB, Figure 2-7) has been developed the furthest; it has been piloted since around 2000 by companies such as Prudent Energy (CN) and Cell strom (AU). The VRFB uses a V2+/V3+ redox couple as oxidizing agent and a V5+/V4+ redox couple in mild sulphuric acid solution as reducing agent. The main advantage of this battery is the use of ions of the same metal on both sides. Although crossing of metal ions over the membrane cannot be prevented completely (as is the case for every redox flow battery), in VRFBs the only result is a loss in energy. In other RFBs, which use ions of different metals, the crossover causes an irreversible degradation of the electrolytes and a loss in capacity. The VRFB was pioneered at the University of New South Wales, Australia, in the early 1980s. A VRFB storage system of up to 500 kW and 10 hrs has been installed in Japan by SEI. SEI has also used a VRFB in power quality applications (e.g. 3 MW, 1.5 sec.).



Schematic of a Vanadium Redox Flow Battery

Hybrid flow battery (HFB)

In a hybrid flow battery (HFB) one of the active masses is internally stored within the electrochemical cell, whereas the other remains in the liquid electrolyte and is stored externally in a tank. Therefore hybrid flow cells combine features of conventional secondary batteries and redox flow batteries: the capacity of the battery depends on the size of the electrochemical cell. Typical examples of a HFB are the Zn-Ce and the Zn-Br systems. In both cases the anolyte consists of an acid solution of Zn2+ ions. During charging Zn is deposited at the electrode and at discharging Zn2+ goes back into solution. As membrane a micro porous polyolefin material is used; most of the electrodes are carbon-plastic composites. Various companies are working on the commercialization of the Zn-Br hybrid flow battery, which was developed by Exxon in the early 1970s. In the United States, ZBB Energy and Premium Power sell trailer-transportable Zn-Br systems with unit capacities of up to 1 MW / 3 MWh for utility-scale applications [iee10]. 5 kW / 20 kWh systems for community energy storage are in development as well.

2.4Chemical energy storage

In this the chemical energy storage focuses on hydrogen and synthetic natural gas (SNG) as secondary energy carriers, since these could have a significant impact on the storage of electrical energy in large quantities (see section 4.2.2). The main purpose of such a chemical energy storage system is to use “excess” electricity to produce hydrogen via water electrolysis. Once hydrogen is produced different ways are available for using it as an energy carrier, either as pure hydrogen or as SNG. Although the overall efficiency of hydrogen and SNG is low compared to storage technologies such as PHS and Li-ion, chemical energy storage is the only concept which allows storage of large amounts of energy, up to the TWh range, and for greater periods of time – even as seasonal storage. Another advantage of hydrogen and SNG is that these universal energy carriers can be used in different sectors, such as transport, mobility, heating and the chemical industry.

Hydrogen (H2)

A typical hydrogen storage system consists of an electrolyzer, a hydrogen storage tank and a fuel cell. An electrolyzer is an electrochemical converter which splits water with the help of electricity into hydrogen and oxygen. It is an end thermal process, i.e. heat is required during the reaction. Hydrogen is stored under pressure in gas bottles or tanks, and this can be done practically for an unlimited time. To generate electricity, both gases flow into the fuel cell where an electrochemical reaction which is the reverse of water splitting takes place: hydrogen and oxygen react and produce water, heat is released and electricity is generated. For economic and practical reasons oxygen is not stored but vented to the atmosphere on electrolysis, and oxygen from the air is taken for the power generation. In addition to fuel cells, gas motors, gas turbines and combined cycles of gas and steam turbines are in discussion for power generation. Hydrogen systems with fuel cells (less than 1 MW) and gas motors (under 10 MW) can be adopted for combined heat and power generation in decentralized installations. Gas and steam turbines with up to several hundred MW could be used as peaking power plants. The overall AC-AC efficiency is around 40 %.

Different approaches exist to storing the hydrogen, either as a gas under high pressure, a liquid at very low temperature, adsorbed on metal hydrides or chemically bonded in complex hydrides. However, for stationary applications gaseous storage under high pressure is the most popular choice. Smaller amounts of hydrogen can be stored in above-ground tanks or bottles under pressures up to 900 bar. For larger amounts of hydrogen, underground piping systems or even salt caverns with several 100 000 m^3 volumes under pressures up to 200 bar can be used. Up to now there has not been any commercial hydrogen storage systems used for renewable energies. Various R&D projects carried out over the last 25 years have successfully demonstrated the feasibility of hydrogen technology, such as a project on the self- sufficient island of Utsira in Norway. Another example is a hybrid power plant from Enertrag in Germany which is currently under construction [ene11]. Wind energy is used to produce hydrogen via electrolysis if the power cannot be directly fed into the grid. On demand, the stored hydrogen is added to the biogas used to run a gas motor. Moreover the hydrogen produced will be used for a hydrogen refilling station at the international airport in Berlin. Water electrolysis plants on a large scale (up to 160 MW) are state-of- the-art for industrial applications; several were built in different locations (Norway, Egypt, Peru etc.) in the late 1990s.

Synthetic natural gas (SNG)

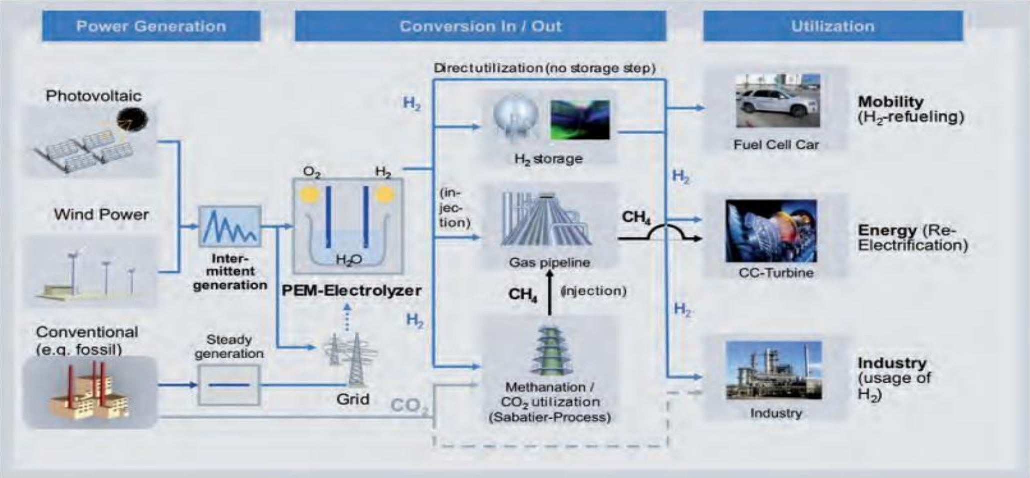
Synthesis of methane (also called synthetic natural gas, SNG) is the second option to store electricity as chemical energy. Here a second step is required beyond the water splitting process in an electrolyzer, a step in which hydrogen and carbon dioxide react to methane in a methanation reactor. As is the case for hydrogen, the SNG produced can be stored in pressure tanks, underground, or fed directly into the gas grid. Several CO2 sources are conceivable for the methanation process, such as fossil-fuelled power stations, industrial installations or biogas plants. To minimize losses in energy, transport of the gases CO2 (from the CO2 source) and H2 (from the electrolysis plant) to the methanation plant should be avoided. The production of SNG is preferable at locations where CO2 and excess electricity are both available. In particular, the use of CO2 from biogas production processes is promising as it is a widely-used technology. Nevertheless, intermediate on-site storage of the gases is required, as the methanation is a constantly running process. Recently this concept "power to methane" has been the subject of different R&D projects (e.g. in Germany, where a pilot-scale production plant is under construction [kuh11]). The main advantage of this approach is the use of an already existing gas grid infrastructure (e.g. in Europe). Pure hydrogen can be fed into the gas grid only up to a certain concentration, in order to keep the gas mixture within specifications (e.g. heating value). Moreover, methane has a higher energy density, and transport in pipelines requires less energy (higher density of the gas). The main disadvantage of SNG is the relatively low efficiency due to the conversion losses in electrolysis, methanation, storage, transport and the subsequent power generation. The overall AC-AC efficiency, < 35 %, is even lower than with hydrogen [ste09]. A comprehensive overview of the combined use of hydrogen and SNG as chemical energy storage is shown in Figure 2-8.

Overall concept for the use of hydrogen and SNG as energy carriers

2.5Electrical storage systems

2.5.1Double-layer capacitors (DLC)

Electrochemical double-layer capacitors (DLC), also known as super capacitors, are a technology which has been known for 60 years. They fill the gap between classical capacitors used in electronics and general batteries, because of their nearly unlimited cycle stability as well as extremely high power capability and their many orders of magnitude higher energy storage capability when compared to traditional capacitors.



This technology still exhibits a large development potential that could lead to much greater capacitance and energy density than conventional capacitors, thus enabling compact designs. The two main features are the extremely high capacitance values, of the order of many thousand farads, and the possibility of very fast charges and discharges due to extraordinarily low inner resistance which are features not available with conventional batteries. Still other advantages are durability, high reliability, no maintenance, long lifetime and operation over a wide temperature range and in diverse environments (hot, cold and moist).

The lifetime reaches one million cycles (or ten years of operation) without any degradation, except for the solvent used in the capacitors whose disadvantage is that it deteriorates in 5 or 6 years irrespective of the number of cycles. They are environmentally friendly and easily recycled or neutralized. The efficiency is typically around 90 % and discharge times are in the range of seconds to hours.

They can reach a specific power density which is about ten times higher than that of conventional batteries (only very-high-power lithium batteries can reach nearly the same specific power density), but their specific energy density is about ten times lower. Because of their properties, DLCs are suited especially to applications with a large number of short charge/discharge cycles, where their high performance characteristics can be used.

DLCs are not suitable for the storage of energy over longer periods of time, because of their high self-discharge rate, their low energy density and high investment costs. Since about 1980 they have been widely applied in consumer electronics and power electronics. A DLC is also ideally suited as a UPS to bridge short voltage failures. A new application could be the electric vehicle, where they could be used as a buffer system for the acceleration process and regenerative braking.

2.5.2Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) systems work according to an electrodynamic principle. The energy is stored in the magnetic field created by the flow of direct current in a superconducting coil, which is kept below its superconducting critical temperature. 100 years ago at the discovery of superconductivity a temperature of about 4 °K was needed. Much research and some luck has now produced superconducting materials with higher critical temperatures. Today materials are available which can function at around 100 °K.

The main component of this storage system is a coil made of superconducting material. Additional components include power conditioning equipment and a cryogenically cooled refrigeration system. The main advantage of SMES is the very quick response time: the requested power is available almost instantaneously. Moreover the system is characterized by its high overall round-trip efficiency (85 % - 90 %) and the very high power output which can be provided for a short period of time.

There are no moving parts in the main portion of SMES, but the overall reliability depends crucially on the refrigeration system. In principle the energy can be stored indefinitely as long as the cooling system is operational, but longer storage times are limited by the energy demand of the refrigeration system. Large SMES systems with more than 10 MW power are mainly used in particle detectors for high-energy physics experiments and nuclear fusion. To date a few, rather small SMES products are commercially available; these are mainly used for power quality control in manufacturing plants such as microchip fabrication facilities.

2.6Thermal storage systems

Thermal (energy) storage systems store available heat by different means in an insulated repository for later use in different industrial and residential applications, such as space heating or cooling, hot water production or electricity generation. Thermal storage systems are deployed to overcome the mismatch between demand and supply of thermal energy and thus they are important for the integration of renewable energy sources.

Thermal storage can be subdivided into different technologies: storage of sensible heat, storage of latent heat, and thermo-chemical adand absorption storage. The storage of sensible heat is one of the best-known and most widespread technologies, with the domestic hot water tank as an example. The storage medium may be a liquid such as water or thermo-oil, or a solid such as concrete or the ground. Thermal energy is stored solely through a change of temperature of the storage medium.

The capacity of a storage system is defined by the specific heat capacity and the mass of the medium used. Latent heat storage is accomplished by using phase change materials (PCMs) as storage media. There are organic (paraffins) and inorganic PCMs (salt hydrates) available for such storage systems. Latent heat is the energy exchanged during a phase change such as the melting of ice. It is also called “hidden” heat, because there is no change of temperature during energy transfer.

The best-known latent heat – or cold – storage method is the ice cooler, which uses ice in an insulated box or room to keep food cool during hot days. Currently most PCMs use the solid-liquid phase change, such as molten salts as a thermal storage medium for concentrated solar power (CSP) plants [iee08]. The advantage of latent heat storage is its capacity to store large amounts of energy in a small volume and with a minimal temperature change, which allows efficient heat transfer. Sorption (adsorption, absorption) storage systems work as thermo-chemical heat pumps under vacuum conditions and have a more complex design.

Heat from a high-temperature source heats up an adsorbent (e.g. silica gel or zeolite), and vapour (working fluid, e.g. water) is desorbed from this adsorbent and condensed in a condenser at low temperatures. The heat of condensation is withdrawn from the system. The dried adsorbent and the separated working fluid can be stored as long as desired. During the discharging process the working fluid takes up low-temperature heat in an evaporator. Subsequently, the vapour of the working fluid adsorbs on the adsorbent and heat of adsorption is released at high temperature.

Depending on the adsorbent/working fluid pair the temperature level of the released heat can be up to 200 °C [sch08] and the energy density is up to three times higher than that of sensible heat storage with water. However, sorption storage systems are more expensive due to their complexity. In the context of EES, it is mainly sensible/latent heat storage systems which are important. CSP plants primarily produce heat, and this can be stored easily before conversion to electricity and thus provide dispatchable electrical energy. State-of-the-art technology is a two-tank system for solar tower plants, with one single molten salt as heat transfer fluid and storage medium.

The molten salt is heated by solar radiation and then transported to the hot salt storage tank. To produce electricity the hot salt passes through a steam generator which powers a steam turbine. Subsequently, the cold salt (still molten) is stored in a second tank before it is pumped to the solar tower again. The main disadvantages are the risk of liquid salt freezing at low temperatures and the risk of salt decomposition at higher temperatures. In solar trough plants a dual-medium storage system.
with an intermediate oil/salt heat exchanger is preferred [tam06]. Typical salt mixtures such as Na-K- NO3 have freezing temperatures > 200 °C, and storage materials and containment require a higher volume than storage systems for solar tower plants. The two-tank indirect system is being deployed in “Andasol 1-3”, three 50 MW parabolic trough plants in southern Spain, and is planned for Abengoa Solar’s 280 MW Solana plant in Arizona. Apart from sensible heat storage systems for CSP, latent heat storage is under development by a German-Spanish consortium – including DLR and Endesa – at Endesa’s Litoral Power Plant in Carboneras, Spain.

The storage system at the pilot facility is based on sodium nitrate, has a capacity of 700 kWh and works at a temperature of 305 °C [csp11]. In adiabatic CAES the heat released during compression of the air may be stored in large solid or liquid sensible heat storage systems. Various R&D projects are exploring this technology [rwe11] [bul04], but so far there are no adiabatic CAES plants in operation. As solid materials concrete, cast iron or even a rock bed can be employed. For liquid systems different concepts with a combination of nitrate salts and oil are in discussion.

The round-trip efficiency is expected to be over 70 % [rad08]. Of particular relevance is whether a pressurized tank is needed for the thermal storage, or if a non-pressurized compartment can be used. In liquid systems, a heat exchanger can be used to avoid the need for a large pressurized tank for the liquid, but the heat exchanger means additional costs and increases the complexity. A dual-media approach (salt and oil) must be used to cover the temperature range from 50 °C to 650 °C. Direct contact between the pressurized air and the storage medium in a solid thermal storage system has the advantage of a high surface area for heat transfer. The storage material is generally cheap, but the pressurized container costs are greater.

2.7 Standards for EES

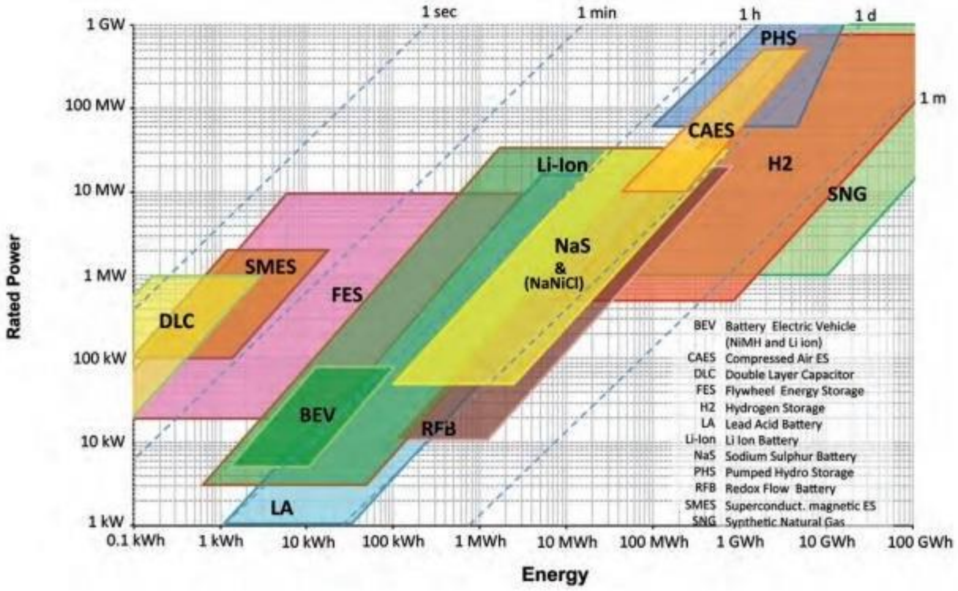
For mature EES systems such as PHS, LA, NiCd, NiMH and Li-ion various IEC standards exist. The standards cover technical features, testing and system integration. For the other technologies there are only a few standards, covering special topics. Up to now no general, technology-independent standard for EES integration into a utility or a stand-alone grid has been developed.

A standard is planned for rechargeable batteries of any chemistry. Standardization topics for EES include:

- terminology
- basic characteristics of EES components and systems, especially definitions and measuring methods for comparison and technical evaluation - capacity, power, discharge time, lifetime, standard EES unit sizes
- communication between components - protocols, security
- interconnection requirements - power quality, voltage tolerances, frequency, synchronization, metering
- safety: electrical, mechanical, etc.
- testing
- guides for implementation.

2.8 Technical comparison of EES technologies

The previous sections have shown that a wide range of different technologies exists to store electrical energy. Different applications with different requirements demand different features from EES. Hence a comprehensive comparison and assessment of all storage technologies is rather ambitious, but in Figure 2-9 a general overview of EES is given. In this doublelogarithmic chart the rated power (W) is plotted against the energy content (Wh) of EES systems. The nominal discharge time at rated power can also be seen, covering a range from seconds to months. Figure 2-9 comprises not only the application areas of today's EES systems but also the predicted range in future applications. Not all EES systems are commercially available in the ranges shown at present, but all are expected to become important. Most of the technologies could be implemented with even larger power output and energy capacity, as all systems have a modular design, or could at least be doubled (apart from PHS and some restrictions for underground storage of H2 , SNG and CAES). If a larger power range or higher energy capacity is not realized, it will be mainly for economic reasons (cost per kW and cost per kWh, respectively).



Comparison of rated power, energy content and discharge time of different EES technologies

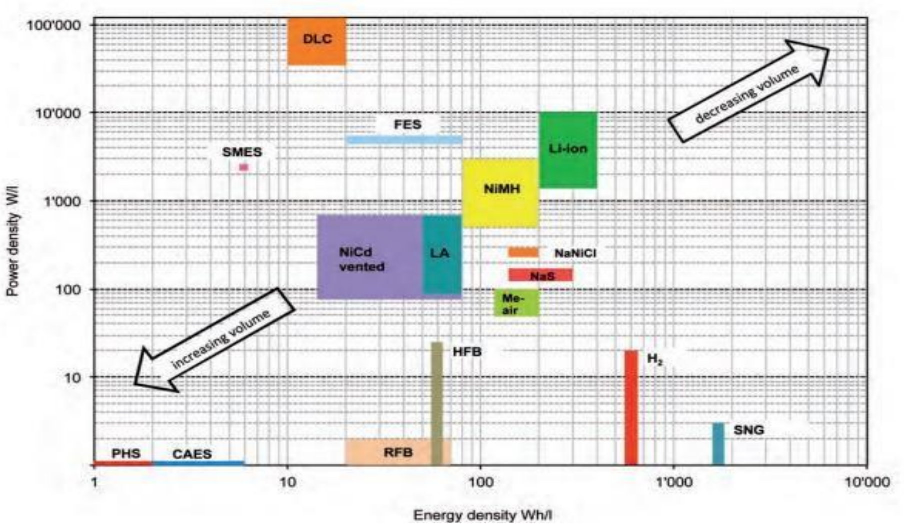
On the basis of Figure 2-9 EES technologies can be categorized as being suitable for applications with:

- Short discharge time (seconds to minutes): double-layer capacitors (DLC), superconducting magnetic energy storage (SMES) and flywheels (FES). The energy-topower ratio is less than 1 (e.g. a capacity of less than 1 kWh for a system with a power of 1 kW).

- Medium discharge time (minutes to hours): flywheel energy storage (FES) and – for larger capacities – electrochemical EES, which is the dominant technology: lead-acid (LA), Lithium ion (Li-ion) and sodium sulphur (NaS) batteries. The technical features of the different electrochemical techniques are relatively similar. They have advantages in the kW - MW and kWh - MWh range when compared to other technologies. Typical discharge times are up to several hours, with an energy-to-power ratio of between 1 and 10 (e.g. between 1 kWh and 10 kWh for a 1 kW system). Batteries can be tailored to the needs of an application: tradeoffs may be made for high energy or high power density, fast charging behaviour or long life, etc.

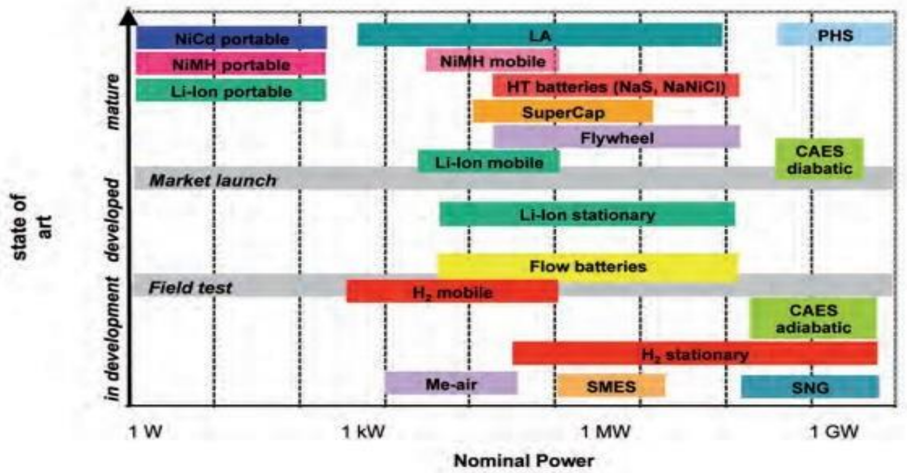
- Long discharge time (days to months): hydrogen (H2) and synthetic natural gas (SNG). For these EES systems the energyto-power ratio is considerably greater than 10. Pumped hydro storage (PHS), compressed air energy storage (CAES) and redox flow batteries are situated between storage systems for medium and long discharge times. Like H2 and SNG systems, these EES technologies have external storage tanks. But the energy densities are rather low, which limits the energy-to-power ratio to values between approximately 5 and 30.

In Figure 2-10 the power density (per unit volume, not weight) of different EES technologies is plotted versus the energy density. The higher the power and energy density, the lower the required volume for the storage system. Highly compact EES technologies suitable for mobile applications can be found at the top right. Large area and volume-consuming storage systems are located at the bottom left. Here it is again clear that PHS, CAES and flow batteries have a low energy density compared to other storage technologies. SMES, DLC and FES have high power densities but low energy densities. Li-ion has both a high energy density and high power density, which explains the broad range of applications where Li-ion is currently deployed. NaS and NaNiCl have higher energy densities in comparison to the mature battery types such as LA and NiCd, but their power density is lower in comparison to NiMH and Li-ion. Metal air cells have the highest potential in terms of energy density. Flow batteries have a high potential for larger battery systems (MW/MWh) but have only moderate energy densities. The main advantage of H2 and SNG is the high energy density, superior to all other storage systems.



Comparison of power density and energy density (in relation to volume) of EES technologies

Figure summarizes the maturity of the storage technologies discussed. The state of the art for each EES technology is plotted versus the power range. Thus the suitability for different applications of the available technologies covered can be compared. Clearly PHS, CAES, H2 and SNG are the only storage technologies available for high power ranges and energy capacities, although energy density is rather low for PHS and CAES. Large power ranges are feasible as these EES systems use the turbines and compressors familiar from other power generation plants. However, only PHS is mature and available. Restrictions in locations (topography) and land consumption are a more severe limit for this technology than the characteristic of low energy density (although the two may be linked in some cases). Figure 2-11 shows a lack of immediately deployable storage systems in the range from 10 MW to some hundreds of MW. Diabatic CAES is well-developed but adiabatic CAES is yet to be demonstrated. Single components of H2 and SNG storage systems are available and in some cases have been used in industrial applications for decades. However, such storage systems become viable and economically reasonable only if the grids have to carry and distribute large amounts of volatile electricity from REs. The first demonstration and pilot plants are currently under construction (e.g. in Europe).



Maturity and state of the art of storage systems for electrical energy

From the technical comparison it can be concluded that a single universal storage technology superior to all other storage systems does not exist. Today and in the future different types of EES will be necessary to suit all the applications described in section 1. Bearing in mind the findings from Figures 2-9 and 2-10, Figure 2-11 suggests the following conclusions. 1) EES systems for short and medium discharge times cover wide ranges of rated power and energy density. Several mature EES technologies, in particular FES, DLC and battery systems, can be used in these ranges. 2) PHS is the only currently feasible largecapacity EES for medium discharge times; further development in CAES is expected. Suitable locations for large PHS and CAES systems are topographically limited. An increase in the capacity of other EES systems, and control and integration of dispersed EES systems (see section 3.3), will be required for medium-duration use. 3) For long discharge times, days to months, and huge capacities (GWh - TWh), no EES technologies have so far been put into practical operation. New EES technologies such as H2 and SNG have to be developed.