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GRID AND STORAGE

Jimmy Ehnberg
Yujing Liu
Maria Grahn
Department of Energy and Environment, Chalmers University of Technology*

* Division of Electrical Power Engineering (J. Ehnberg, Y. Liu), Division of Physical Resource Theory (M. Grahn)
Chapter reviewers: Ola Carlson and David Steen, Electrical Power Engineering, Chalmers University of Technology.

INTRODUCTION

Large scale introduction of renewables will change the requirements on the electrical grid. The grid will need to handle electricity production at new locations and the variation in time of electricity generation will change as well (see Chapter 4 and 9). Increased variations in power flow, both in amplitude and direction, will also require new types of control and protection of the grid.

The intermittent behaviour of the major renewables, i.e. solar and wind, requires either complementary power sources that can balance power supply (Chapter 11), a shift in energy demand (Chapter 10) or deployment of electrical storage. Storage can also limit or delay the need for grid extension and reinforcement and help solving control and protection issues.

There is a wide range of storage technologies and the choice of technology is dependent on which problem to solve, and in many cases, what resources are locally available. Figure 5.1 indicates discharge time and typical power capacity per unit for a range of storage technologies. Technologies that store a large amount of energy for long a time are suitable for shifting energy supply in time and thereby reducing the need for grid extension; technologies with a short response time can be used to mitigate power quality problems. One can note that for stationary applications like energy storage systems connected to the grid, weight, and in most cases also volume, are of the less importance, as compared to energy storage in vehicles[1]. Therefore alternatives like pumped hydro and compressed air are commonly applied for large-scale and long-term (hours to days) energy storage. However, pumped hydro has geographical requirements and technical and economical limitations that limits its application.

1 See *Systems Perspectives on Electromobility.* (2014) 2nd edition. Chalmers Univeristy of Technology, Göteborg, Sweden

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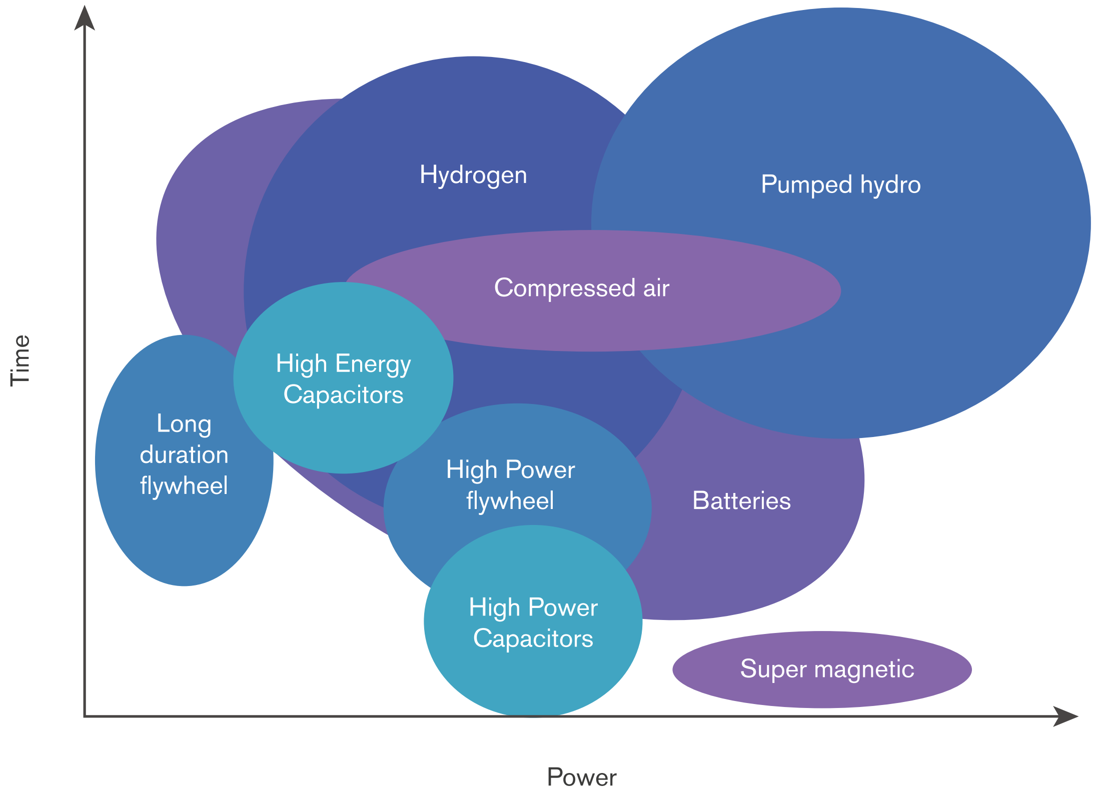

Figure 5.1 Discharge time and different available capacity rates for storage technologies. The figure is only indicative. The time scale is logarithmic from seconds to months and the power scale is logarithmic from kW to GW.

Off-grid systems are systems for an isolated area like an island or a village or even a house or a single device. These are mainly used where connection to the national, or local grids, are too expensive. The interest in off-grid systems has increased due to the decrease in cost of small-scale renewables, like solar panels and small wind turbines. To balance demand and supply in an off-grid system a combination of several energy sources is beneficial but in most cases energy storage systems are required.

This chapter contains a short overview of the basic functions of grids for renewables as well as a short description of current and future technologies for electricity storage. The chapter also includes a brief discussion on more unconventional ways of looking at electricity storage.

THE ELECTRICAL GRID AND CONNECTION OF RENEWABLES

A grid is a network used for transmission and distribution of electricity. The grid can be divided into three levels: the transmission, subtransmission and local grid. The transmission grid is the highways of electricity used to transmit large amount of power long distances, e.g. to supply one part of the country with electricity produced in another part. The transmission grid uses high voltage (> 200 kV) to limit losses, which makes all installations very costly and requires a lot of space. The transmission grid is normally built and operated in a way that power can take other ways through the system during maintenance or if something goes wrong (the grid is meshed). This redundancy is important since a lot of people will be affected if the transmission system goes out of operation. Only very large production units (hundreds of MW) are connected to the grid at this level.

The subtransmission grid is used to distribute electricity in a part of a country. Power is distributed in a meshed grid at lower voltage then in the transmission grid (70 - 130 kV) to limit the cost of installation and the space required. The redundancy at this level is the same as at the transmission level. Large production units (tens of MW) and very large consumers (above tens of MW) are connected at this level.

The local grid consists of two parts: a medium voltage part (10 - 30 kV) and a low voltage part (110 – 400 V). The medium voltage grid is used to distribute electricity from the nodes of the subtransmission grid to large consumers and production units (100 kW to a few MW). The medium voltage grid is normally built in rings but operated radially. This allows the system to be reconnected in a different configuration after faults, however, not automatically. This gives a redundancy but costumers and productions units will experience short interruptions. For planned outages, reconnection can normally be done to avoid even short interruptions. The low voltage system is used for distribution of electricity for blocks and small neighborhoods. At this levels, single household consumers, small business consumers and small production units (< 100 kW) are connected.

The above mentioned grids are interconnected at a substation that both handle the voltage transformation between the levels and works as nodes in the grids. In the substations also control and protection units are placed. Normally it is the capacity of the transformation that is the limiting factor at a substation.

The figures indicating what capacities of production and consumption units can be connected at the different grid levels are only indicative and highly dependent on the local conditions of the grid or even on individual lines and transformers. When planning for connecting renewables to the grid also the direction of the power is important and the local balance between demand and supply. From this perspective, renewables should be connected at as low voltage level as possible in order to use the grid efficiently and avoid jeopardising the reliability of larger parts of the system.

From the perspective of efficient grid operation, there are positive as well as negative effects of high penetration of renewables. For the introduction of renewables, the existing grid is mainly beneficial. However, as renewable electricity production expands, fundamental changes in the system will be required.

The main idea used today when dimensioning the grid is that the size of the grid connection is based on the installed production capacity, independently of the number of utilisation hours. This means that there should always be grid capacity available for full electricity production even though there is not always production available. To reduce investments in new power lines and substations and thereby reduce cost and environmental intrusion, production limitations (curtailment), or distributed storage systems could be used in future (see also Chapter 9-10 and 12).

To reduce losses in the grid, renewables should also be connected (normally also located) as close as possible to consumption. The losses in the grid are highly dependent on the geographical distribution of production and consumption. In Sweden, which has an oblong system, with much production in the north and the main part of the consumption in the south, the total losses in the system are up to 10 %. A large number of small scale renewables could utilise the current grid more efficiently, and may even reduce overall losses, if they are located close to consumers.

Since all parts of the grid are interconnected, all things will affect each other, and since the functioning of the grid is critical to society, there are a number of requirements on all grid connections. The requirements on renewables are depending on where in the system they will be connected but also on the size of the installation. Renewables connected to the transmission and sub transmission grid will have large impact of the national grid and therefore national regulation is set to secure operation of the grid. The national regulations are normally called grid codes and set by the transmission system operator. There might also be additional requirement to secure local compatibility.

Renewables connected to the local grids are of less importance to operation of the national grid. Some parts of the grid codes still apply but the local grid codes are more important since they emphasise the compatibility with nearby installations, both costumers and other production units.

In general, the cost of expanding the grid shall be paid by the one who requires an upgrade, but on the other hand, if capacity is available no connection cost will be charged. Under certain circumstances, this will cause a threshold effect. Someone has to take a large initial capital investment while the following will benefit from it, since most often it is not possible to make an extension of the system that will fit only the need for the one who wishes to connect. In addition, upgrades far away from the installation may be needed to maintain the possibility to use a meshed grid and to keep the desired level of redundancy. This could make the threshold even higher.

STORAGE AS A COMPLEMENT TO RENEWABLES

The intermittent behaviour of the major renewables may create problems when they replace production with more constant generation (see Chapter 3, 4, 9 and 11). A major concern is to what extent it is possible to compensate for frequency changes in the grid fast enough (Figure 9.1). This can, however, be solved by the fast reactions of some storage technologies (Figure 5.1).

Storage installations can also be used to reduce, or delay, the need for grid extensions. Energy shift electricity storage localised close to bottlenecks in the grid can be charged when there is a risk of overload and discharge when there is free capacity in the bottleneck. With very high levels of renewables, storage technologies could also be used to shift energy supply over longer time frames (weeks and months).

Electricity storage can also be used as an uninterruptable power source that will supply a load when the grid is out of operation. Since many of the storage technologies require a frequency converter to charge and discharge they can serve other purposes too. The converters can be used for power quality problem mitigation like voltage control, harmonics and voltage dip mitigation. By production or consumption of reactive power they may also reduce losses in the grid.

STORAGE TECHNOLOGIES

There is a variety of technologies available today and some are more useful as complement to renewables and grid support then others. In these applications, cost, reliability and lifetime is more important than weight. Normally, volume is not a limiting factor for grid connected electricity storage either, but in some urban or in-house applications it might be. Therefore the low cost alternatives like pumped hydro and compressed air are commonly applied for large-scale and long-term (hours to days) energy storage.

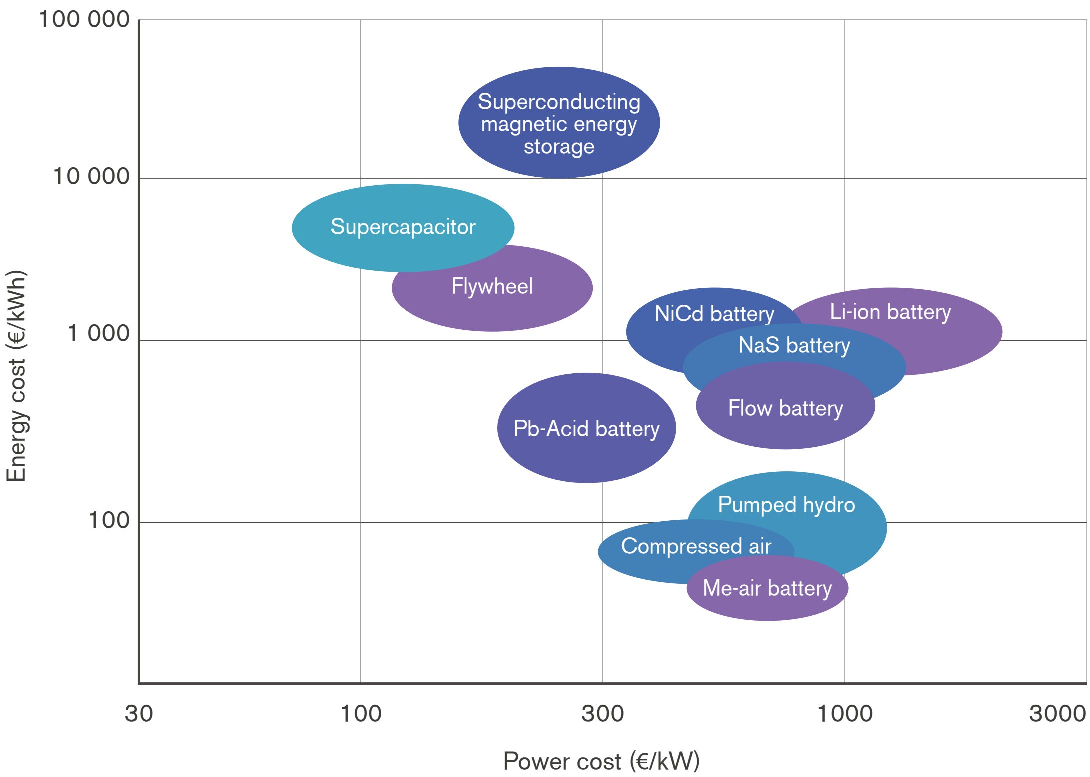

Figure 5.2 Costs of different energy storage technologies.

PUMPED HYDRO STORAGE

The basic principle of pumped hydro energy storage (PHES) is to store electricity by pumping up water to a reservoir, convert it to hydraulic potential energy, and then release the power when needed.

There are two main types of PHES: pure PHES, also known as closed-loop or off-stream PHES, and pump-back PHES. The pure PHES is a technology based on a closed water system where the same water is reused in the system continuously. A sketch of the basic principle for a pure PHES can be seen in Figure 5.3.

A pump-back PHES is a combination of a conventional hydropower system with a natural flow through the system where the PHES utilises the capacity in the dam and the turbine.

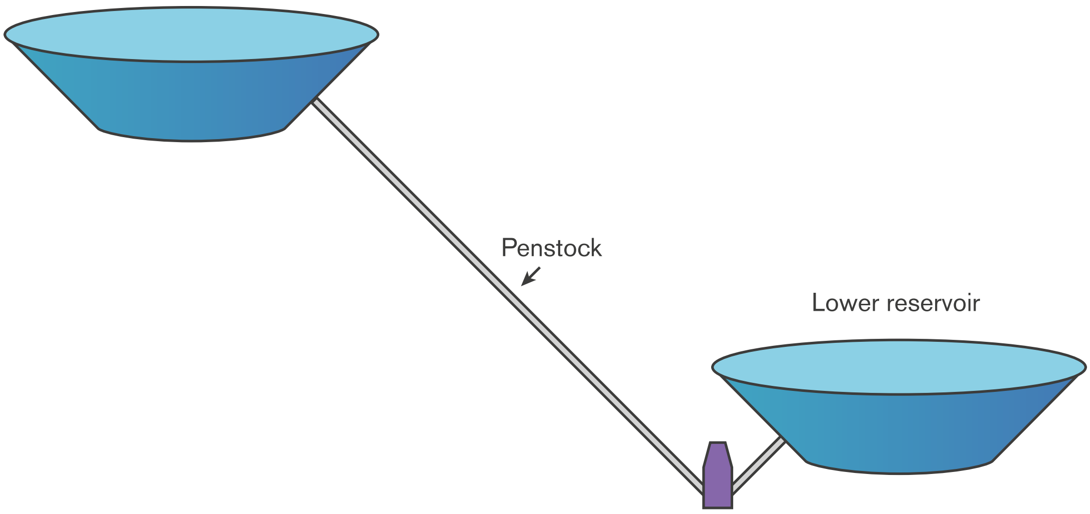

Figure 5.3 Basic principle for pure pumped hydro energy storage

PHES is a mature technology and is currently the only commercially proven energy storage technology for large scale (>100 MW) storage. Today more than 300 plants are installed worldwide with a total installed capacity of more than 95 GW. The dominant users of PHES are Japan and USA, with approximately 50 % of the installed capacity worldwide. The round trip efficiency is about 60-75%.

PHES was mainly installed during the 1960s to 1980s as an energy reserve due to the increased use of nuclear power. The PHES were installed for control and to allow optimum use of the nuclear power reactors. The installation rate has now declined since the best locations have already been exploited. However, the interest of new installations is expected to increase with the growth of intermittent renewable power. PHES are suitable for services like energy shift and frequency stabilisation.[2]

The major disadvantage of PHES is the requirement for special site conditions. It requires two large reservoirs, except for seawater systems that only require the upper basin but then instead needs to be close to a shore with an elevation difference. The environmental effects are believed to be similar to normal hydro-power plant, but the water level in the reservoir(s) will change more drastically (see Chapter 6).

There is an ongoing development of PHES technology. By varying the speed of the pump, the PHES can be used for control purposes also during pumping and the efficiency could increase. The expected increase in installation cost is

2 Deane, J.P. et al. (2010) Techno-economic review of existing and new pumped hydro energy storage plant, *Renewable and Sustainable Energy Reviews*, 14(4):1293-1302.

approximately 5%. Furthermore, a change to a multiblade turbine pump runner has shown to increase the efficiency by 4%. In Japan, tests have also been conducted with sea-water PHES that utilises sea water and is expected to lower the civil construction costs and increase the number of available sites; however, there is a concern for increased corrosion due to the salinity.

COMPRESSED AIR STORAGE

Compressed Air Energy Storage (CAES) is a technology to store energy as compressed air. CAES is suitable for balancing energy daily. In terms of air storage approaches, CAES can be divided into underground air storage and above-ground air storage.

The underground system uses a compressor to pressurise air and pump it into underground geological formations like caverns in abandoned salt mines, see Figure 5.4.

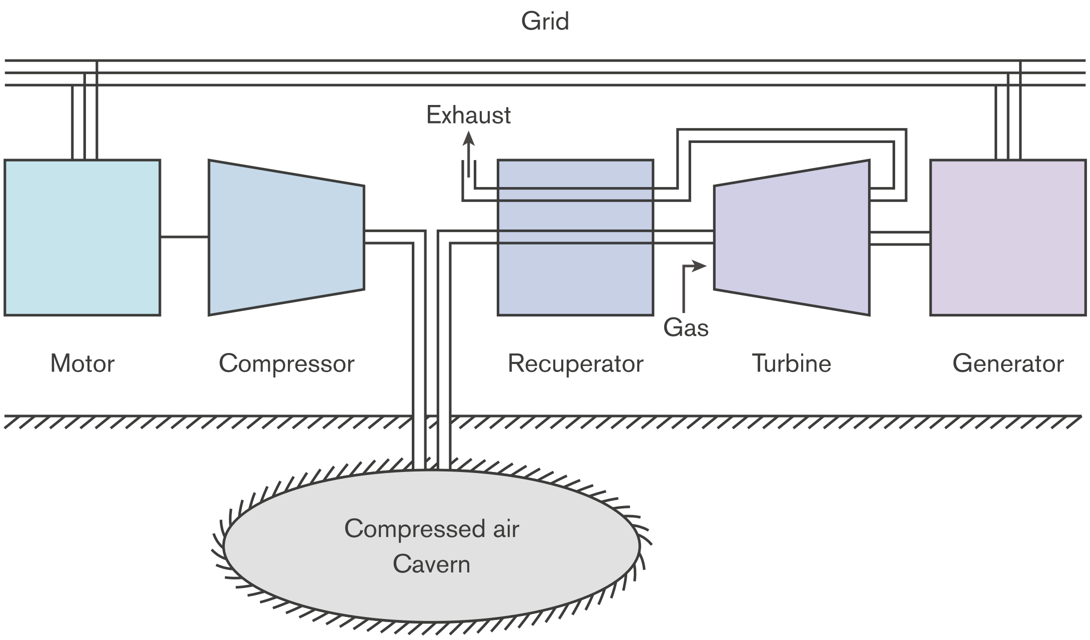

Figure 5.4 Large-scale compressed air energy storage (underground)

Air is compressed and pumped into the caverns when energy demand is low. The pressurised air is then released through a recuperator (a kind of heat exchanger) and heated with small quantities of natural gas or biogas to drive a gas turbine to provide electric power to the grid through a generator when needed.[3] This technology is mainly used for large-scale energy storage with a power capacity of 100-300 MW. The appeal of underground CAES is that it is cost-effective for large installations. But the suitable locations with right size cavern can be hard to find. The first commercial CAES was installed in Huntorf, Germany in 1978 with a power capacity of 290 MW for three hours.[4] Another plant with 110 MW power capacity and duration of 26 hours was built in 1991 in McIntosh, Alabama, USA. Both plants use old salt caverns.

3 Vadasz, P. (2009) Compressed air energy storage. In *Energy Storage System* (ed. Gogusay, Y. A.) Paris, France: EOLSS publishers.

4 Crotogino, F., et al. (2001) Huntorf CAES: More than 20 Years of Successful Operation. *SMRI Spring Meeting*. 351-362 Orlando, FL, USA, Apr. 15-18.

Another CAES technology relies on above ground air storage. Pressurised air is stored in man-made high-pressure containers, tanks or pipes. The storage can be placed where needed, for example, close to wind or solar farms.[5] CEAS may thus offer an alternative to upgrading lines allowing for a more even transmission of power. An optimal configuration of an above ground CAES is currently believed to have a capacity of 10-30 MW and a storage duration time of 4-6 hours. An above ground 9 MW CAES is planned to be installed in Queens, New York. The system utilises steel pipes and a modular structure. The duration at rated power is 4.5 hours. The incentives for the installation include frequency regulation and energy shift. The round trip efficiency is about 60-75%.

The next generation of CEAS technology is expected to be Isothermal Compressed Air Energy Storage (ICAES). ICEAS increases the efficiency of the thermodynamic cycle, by compressing and expanding air at near-constant temperature. For further simplicity, the compressor and the expander can be the same machine. Another advantage is that the process does not require natural gas or biogas, see Figure 5.5. The future role of CAES in energy storage is promising, in particular for solutions that manage to combine modularity and cost-effectiveness. The market is expected to grow significantly in the near future.

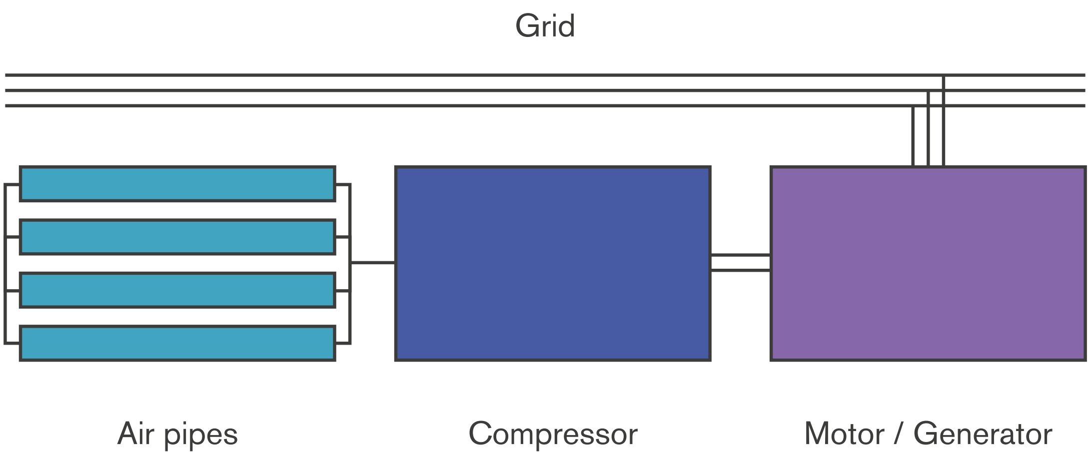

Figure 5.5 Isothermal compressed air energy storage (above-ground)

BATTERIES

Seven battery types are described in this section, most of them technologically mature. The comparison is mainly based on data from a white paper from 2011[6] and the Encyclopedia of Electrochemical Power Sources.[7]

Lead acid (PbA) batteries have been commercially available for more than hundred years and offer a mature technology at low cost. PbA battery systems are used in both stationary and mobile applications. They are typically used as starter batteries in vehicles, emergency power supply systems or in stand-alone solar photovoltaic systems. In the period 1910 to 1945, PbA batteries were used for storing electricity in grids. Disadvantages of PbA batteries are, e.g., relatively low energy density,

5 Le, H. and Santoso, S. (2013) Operating compressed-air energy storage as dynamic reactive compensator for stabilizing wind farms under grid fault conditions. *IET Renewable Power Generation,* 7(6):717-726.

6 IEC (2011) *Electrical Energy Storage* White Paper, Geneva, Switzerland :International Electrotechnical Commission (IEC).

7 Garche, J. ed. (2009) *Encyclopedia of Electrochemical Power Sources*. Amsterdam, The Netherlands: Elsevier.

see Figure 5.2, and the content of lead, a hazardous material often prohibited or restricted. Advantages are the favourable cost, see Figure 5.3, recyclability, and simple charging.

Nickel cadmium (NiCd) batteries have been in commercial use for almost hundred years whereas nickel metal hydride (NiMH) batteries became commercially available about twenty years ago. Compared to PbA batteries, nickel-based batteries have a higher power density, a slightly higher energy density and withstand more charge and discharge cycles. NiCd batteries are, as PbA batteries, capable of performing well even at low temperatures, down to -40°C. However, because of the toxicity of cadmium, these batteries are, since 2006, prohibited for consumer use in Europe. NiMH batteries were developed to replace NiCd batteries and have similar properties as NiCd batteries but higher energy densities. NiMH batteries are considered more robust and safer than Lithium ion batteries but cost about the same.

Lithium ion (Li-ion) batteries are mainly used in mobile applications such as laptops, cell phones, and electric bicycles. Li-ion batteries generally have a high efficiency and are very flexible, where almost any discharge time from seconds to weeks can be obtained. Standard cells can handle more full cycles than many other battery options. Safety is, however, a serious issue and to improve the safety, Li-ion battery batteries are equipped with a monitoring unit to avoid over-charging and over-discharging[8]. Due to these special packaging and protection circuits, Li-ion batteries are currently costly, see Figure 5.3. The Li-ion battery technology is still developing, and there is considerable potential for further progress.

Sodium sulphur (NaS) batteries consist of molten sulphur at the positive electrode and molten sodium at the negative electrode and to keep the electrodes in a liquid form the battery temperature is kept in the range 300-350°C. NaS batteries typically have a discharge time of 6-7 hours and a fast response, in the range of milliseconds, indicating that NaS batteries meet the requirements for grid stabilisation. A major drawback is that a heat source is required to maintain operating temperatures.

The sodium nickel chloride (NaNiCl) battery, also known as the ZEBRA (Zero Emission Battery Research) battery, has been commercially available for the last twenty years. It is a high-temperature battery with an operating temperature slightly lower than the NaS battery (around 270 °C). It uses nickel chloride instead of sulphur at the positive electrode. Compared to NaS batteries, NaNiCl batteries have better safety characteristics, higher cell voltage and can withstand limited over charge and discharge.

A metal air (Me-air) electrochemical cell consists of an anode made from pure metal and a cathode connected to air (oxygen). Among the various Me-air batteries the lithium air battery is the most attractive since its theoretical specific energy is about 100 times higher than most other battery types. However, the mix of lithium and humid air can cause fire, which is a safety risk. Currently only a zinc air battery

8 See *Systems Perspectives on Electromobility*. (2014) 2nd edition. Chalmers Univeristy of Technology, Göteborg, Sweden

is technically feasible. A rechargeable Me-air battery system potentially offers low material cost and high specific energy, but no Me-air battery type is commercially available yet.

A flow battery is a type of battery that was originally developed by NASA in the early 70s for space flights. The electrolytes are stored externally in tanks and pumped through an electrochemical cell that converts chemical energy directly to electricity and vice versa. The power is defined by the size and design of the cell whereas the energy depends on the size of the tanks. Flow batteries can be fitted to a wide range of stationary applications including storing energy for durations of hours or days with a power of up to several MW. Flow batteries are classified into redox flow batteries (RFB) and hybrid flow batteries (HFB), combining features of conventional batteries and RFBs. Theoretically an RFB can be recharged within a few minutes by pumping out the discharged electrolyte and replacing it with recharged electrolyte. Both RFBs and HFBs are under development where HFBs have been tested in units up to 1 MW (3 MWh).

A comparison of the level of maturity, energy efficiency, and approximate amount of possible recharging cycles of the different batteries are provided in Table 5.1.

Table 5.1 Comparison main features of different battery types.

Battery type	Commercially available	Round trip efficiency	Approximate cycle life
Lead acid (PbA)	1890	50-92%	500-1500
Nickel cadmium (NiCd)/ Nickel metal hydride (NiMH)	1915/1995	70-90%	2500
Lithium ion(Li-ion)	1990	80-98%.	1000-10 000
Sodium sulphur (NaS)	1990	75%	2500-4500
Sodium nickel chloride (NaNiCl)	1995	89-92%	2500-4500
Metal air (Me-air)	Not yet commercial	n.a.	n.a.
Flow (RFB, HFB)	Not yet commercial	n.a.	n.a.

Today, mainly Lead acid and Lithium ion are used in the small storage systems that exist. The battery types show different characteristics and from the comparison it seems like Sodium sulphur (NaS), Sodium nickel chloride (NaNiCl) and flow batteries could be most promising options for balancing the grid and store electric power. However, since the major concern is the cost of the battery also reuse of traction batteries is often discussed as a viable option for electricity grid storage. The technology choice will then depend on what is used in electric cars.

HYDROGEN STORAGE

A typical hydrogen storage system consists of an electrolyser, a hydrogen storage tank and a fuel cell. An electrolyser is an electrochemical converter that splits water, with the help of electricity, into hydrogen and oxygen. Hydrogen is most often stored under pressure in gas bottles or tanks. To generate electricity, hydrogen and oxygen react in a fuel cell (forming water vapour). It is also possible to use gas motors, gas turbines or combined cycles of gas and steam turbines, instead of a fuel cell, when producing electricity from hydrogen.

Current electrolysers (alkaline) have a conversion efficiency of 60-70%, but high temperature solid oxide electrolysers (SOECs), which are expected to enter the market 2015-2020,[9] are assumed to have an efficiency of more than 70%. Hydrogen has the advantage of being a universal energy carrier, meaning that it can also be sold to other energy sectors, such as transport, heating and to the chemical industry. Challenges for commercial hydrogen storage systems are that the electrolyser must be able to operate intermittently and that the system has to be competitive compared to other electricity storage options. The round trip efficiency is 20-45%.

Various R&D projects carried out over the last 25 years have demonstrated the feasibility of hydrogen storage technology. One example is a hybrid power plant in Germany (Enertrag) which is currently under construction.[10] The plant will produce electricity from wind energy and from biogas in a gas turbine. When the wind power is not directly fed into the grid (when the electricity price is low) it will instead be used to produce hydrogen via electrolysis. When the electricity price is high the stored hydrogen will be converted back into electricity in the gas turbine.

FLYWHEEL

A flywheel energy storage system (FESS) consists of a mechanical rotating wheel, a drive motor, a retaining container, and control devices. The kinetic energy stored in the rotational flywheel is proportional to its inertia and the square of its rotating speed. To charge a FESS, the motor will convert electrical energy to mechanical energy by applying a torque and speed up the flywheel. To discharge the flywheel, the motor will act as a generator and convert the mechanical energy in the system to electrical energy. FESS can be used in power systems for voltage support, provision of system inertia and power quality.[11]

Conventional flywheels are made of high strength steel and have high rotational inertia and rotate at the speed around 3000-5000 rpm (revolutions per minute). The maximum size of the flywheels is limited by tensile strength and homogeneity of the steel.

FESS has the advantages of high power density, high number of discharging cycles, long lifetime, low lifecycle costs and use of conventional materials. The rotating systems are more robust and easy to control. The round trip efficiency is 80-85%.

9 Brisse, A. (2013). Key technologies: Solid Oxide Electrolyzer Cell, CO_2 Electrofuels seminar, *European institute for energy research (EIFER)*, Iceland, Jun. 12.

10 See Enertrag (2014). *Hybrid power plant.*

11 Suvire, G.O. and Mercado, P.E. (2012). Active power control of a flywheel energy storage system for wind energy applications. *IET Renewable Power Generation*, 6(1):9-16;
Eyer, J. and Corey, G. (2010). *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide - A Study for the DOE Energy Storage Systems Program.* Albuquerque, NM, USA and Livermore, CA, USA: Sandia National Laboratories (SAND2010-0815)

In the last decade, a new technology is developed together with the advance of material technology, power electronics, and design techniques. A high-speed low-inertia flywheel is made of carbon fibre and rotates at much higher speed than conventional flywheels. The motor can be integrated within the flywheel to improve rotor dynamics and make it more compact. To reduce the air friction losses due to high speed, the flywheel is usually encapsulated in a vacuumed chamber. The oil-filmed magnetic bearings are replaced by contactless magnetic bearings. The entire flywheel and the rotor of the motor are magnetically levitated in the vacuum. The power flow in or from the flywheel is controlled by power electronics.

A high-speed flywheel with a weight of only a few kilograms can reach a power of about 200 kW at 50 000 rpm. An array of hundreds of flywheel units can form a 20-50 MW energy storage station. Even though the carbon fibre composite flywheels have high mechanical strength and low weight, the steel flywheels are still preferred as low-cost and reliable alternatives.

SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Magnetic energy is often used as an intermediate energy form in a lot of energy conversion apparatuses, such as generators, transformers and motors.

In order to increase the energy density to a competitive level, the magnetic field intensity needs to increase. This is accomplished in Superconducting Magnetic Energy Storage (SMES) that is comprised of a superconducting coil, a power electronic converter, and a cooling system.

SMES is divided in low temperature superconducting (LTSC) and high temperature superconducting (HTSC) devices. The former is related to the conventional superconductors that become superconducting below a temperature of 20 K, or -253 °C. High temperature superconducting (HTSC) was discovered in 1986. The highest temperature for which superconducting has been recorded is 138 K, or -135 °C, reported in 2009. To maintain such extreme temperatures a cryogenically cooled refrigerator is needed. Even though the operating losses of the cooling system do not significantly influence system efficiency, the extra equipment makes the system more complicated and expensive.

One advantage of SMES is its very short response time (<100 ms). SMES is therefore suitable for improving grid stability of distribution and power quality in local networks. Another advantage of SMES is its high round trip efficiency (up to 95%). Finally, the main components are stationary, without moving parts, which contributes to high operational reliability.

SMES is still costly compared to other energy storage systems. The superconducting ceramics used in the coils is still a key issue for SMES due to high temperatures they have to resist. Recent developments focus on the costs of manufacturing the wires and increasing the current density and mechanical strength. The supporting mechanical structure is another challenge for large-scale SMES. Integration into power units may increase the competitiveness.[12]

12 Nielsen, K.E. (2010) *Superconducting magnetic energy storage in power systems with renewable energy sources*. Master Thesis, Norwegian University of Science and Technology.

SUPER CAPACITORS

Supercapacitors (SC) are electrochemical capacitors and are also called ultracapacitors or electric double-layer capacitors. Supercapacitors can be considered as a mix between conventional capacitors and batteries. They have much higher energy density than conventional capacitors, but much lower than any battery. Because of their high speed of charging and discharging, supercapacitors have 10-100 times higher power density than conventional batteries and the round trip efficiency is about 70-80%.

Supercapacitors have already found wide applications in consumer and industrial products like laptop computers, GPS, and other mobile devices and tools. With the advantages of fast charging and long cycle life, supercapacitors are used as alternatives to batteries in cable cars, wind turbines pitch systems, and motor starts for diesel vehicles. For energy recovery in trains, trams, busses, and electric or hybrid vehicles, supercapacitors are used in combination with batteries to increase energy efficiency and prolong the battery lifetime.

Supercapacitors are one of the most promising technologies for short-term energy storage. Research on new materials is intense and includes exploration of nanotube electrodes, graphene electrodes, and lithium-ion supercapacitors.

OTHER WAYS OF STORING ENERGY

There are many different ways to store energy. So far, we have discussed technologies where electricity is converted, stored and converted back to electricity again, but there are also other options.

Hydropower dams are the most common way to store energy (potential energy) that later are to be used for electricity production. The system can be made in large scale and with a high efficiency but the environmental effects might be considerable (see Chapter 6). Due to its advantages, hydropower with large dams is often used to control the grid wherever it is possible (Chapter 11).

There are also other ways where energy can be stored for later conversion into electricity. One example is thermal energy storage in concentrated solar thermal power plants (CSP) where excess solar energy can be stored in molten salts (Chapter 4). The advantage is the capacity to store large amounts of energy in a small volume and with a minimal temperature change, which allows efficient heat transfer. In Seville, Spain, the thermal storage system extends the daily electricity generation to over 12 hours in winter and up to 20 hours in summer. Disadvantages are the risk of liquid salt freezing at low temperatures and the risk of salt decomposition at higher temperatures. For liquid systems different concepts with a combination of nitrate salts and oil are under discussion. The round trip efficiency can exceed 70%.

By introduction of some reserve production and storage of produced goods, almost all manufacturing may be used as electricity storage. This is often referred to as demand side management (Chapter 10).

One example of a process with a kind of inbuilt storage capacity is to convert the excess electricity via hydrogen to carbon based fuels such as synthetic natural gas (SNG) or methanol, so called electrofuels. These fuels can be stored and later be used in the transportation sector or as feedstock in the chemical industry and can utilise existing infrastructure (Chapter 12).

CONCLUDING REMARKS

The grid needs to adapt to the new situation with a large amount of renewables in the near future. The need for grid extension can be limited by introduction of electricity storage. Storage technology can have multiple uses in the electric grid system which complicates any comparison between different storage technologies. Electricity storage technologies not only have to compete with each other but also with other means to solve grid balancing issues. Examples are systems where energy can be stored before it is converted into electricity and systems where electricity is converted to some storable goods that can be used when needed and, finally, systems that apply curtailment of production.

Today there are very few incentives to install storage or sell storage-like services; however, with larger power fluctuation on the grid and price fluctuations on the power market that can be expected with a large scale introduction of renewables, the demand for new solutions will grow.