CHAPTER 21

Wind energy storage technologies

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Energy storage is widely recognised as a key enabling technology for renewable energy and particularly for wind and photovoltaics. Distributed generation could also help, but the location of wind resources and consumption are almost mutually exclusive. The main thrust of the US DoE Energy Storage Programme ($615 M) is in the direction of batteries and CAES. Advanced battery storage (electric vehicles (EV), flow batteries, second-life EV batteries) has the potential to reduce the need for grid infrastructure as it is not topographically, geologically and environmentally limited. This chapter includes a brief examination into the energy storage techniques currently available to assist large-scale wind penetrations. These are pumped-hydroelectric energy storage (PHES), underground pumped-hydroelectric energy storage (UPHES), compressed air energy storage (CAES), battery energy storage (BES), flow battery energy storage (FBES), flywheel energy storage (FES), supercapacitor energy storage (SCES), superconducting magnetic energy storage (SMES), hydrogen energy storage system (HESS), thermal energy storage system (TESS) and finally, EVs. The objective was to identify the following for each: how it works; advantages; applications; cost; disadvantages and future potential.

A brief comparison was then completed to indicate the broad range of operating characteristics available for energy storage technologies. It was concluded that PHES/UPHES, FBES, HESS, TESS and EVs are the most promising techniques to undergo further research. The remaining technologies will be used for their current applications in the future, but further development is unlikely.

1 Introduction

Traditional electricity networks are supplied by large, centralised and highly predictable generating stations. An inherent characteristic of such networks is that supply must meet demand at all times. Typically matching supply with demand on a network requires backup sources of power, such as an open-cycle gas turbine,

WIT Transactions on State of the Art in Science and Engineering, Vol 44, © 2010 WIT Press
www.witpress.com, ISSN 1755-8336 (on-line)
doi:10.2495/978-1-84564-205-1/21

or by a storage system. Wind energy is inherently intermittent, variable and non-dispatchable (cannot be switched on 'on demand'). Consequently, the need for such backup sources of power increases as the proportion of wind generation on the system increases. To reduce fuel demands, it is desirable that the backup source is a storage facility rather than further primary generation. In this chapter we will discuss the various options for electricity storage including both large-scale centralised storage and smaller-scale distributed storage.

Storage systems such as PHES have been in use since 1929 [1], primarily to level the daily load on the electricity network between night and day. As the electricity sector is undergoing a lot of change, energy storage is becoming a realistic option [2] for: restructuring the electricity market; integrating renewable resources; improving power quality; aiding the shift towards distributed energy; and helping the network operate under more stringent environmental requirements. In addition, energy storage can optimise the existing generation and transmission infrastructures whilst also preventing expensive upgrades. Power fluctuations from renewable resources will prevent their large-scale penetration into the network. However energy storage devices can manage these irregularities and thus aid the amalgamation of renewable technologies. In relation to conventional power production, energy storage devices can improve overall power quality and reliability, which is becoming more important for modern commercial applications. Finally, energy storage devices can reduce emissions by aiding the transition to newer, cleaner technologies such as renewable resources and the hydrogen economy. Therefore, Kyoto obligations can be met (and penalties avoided). A number of obstacles have hampered the commercialization of energy storage devices including: a lack of experience – a number of demonstration projects will be required to increase customer's confidence; inconclusive benefits – consumers do not understand what exactly are the benefits of energy storage in terms of savings and also power quality; high capital costs – this is clearly an issue when the first two disadvantages are considered; responsibility for cost – developers view storage as 'grid infrastructure' whereas the Transmission System Operator (TSO) views it as part of the renewable energy plant.

However, as renewable resources and power quality become increasingly important, costs and concerns regarding energy storage technologies are expected to decline. This chapter identifies the numerous different types of energy storage devices currently available. The parameters used to describe an energy storage device and the applications they fulfil are explored first. This is followed by an analysis of each energy storage technology currently available indicating their: operation and the advantages; applications; cost; disadvantages; future; and finally, a brief comparison of the various technologies is provided.

2 Parameters of an energy storage device

Below is a list of parameters used to describe an energy storage device. These will be used throughout the chapter:

- *Power capacity* is the maximum instantaneous output that an energy storage device can provide, usually measured in kilowatts (kW) or megawatts (MW).

- *Energy storage capacity* is the amount of electrical energy the device can store, usually measured in kilowatt-hours (kWh) or megawatt-hours (MWh).
- *Efficiency* indicates the quantity of electricity that can be recovered as a percentage of the electricity used to charge the device.
- *Response time* is the length of time it takes the storage device to start releasing power.
- *Round-trip efficiency* indicates the quantity of electricity which can be recovered as a percentage of the electricity used to charge and discharge the device.

In addition to the above, the following parameters are also used in describing rechargeable batteries and flow batteries:

- *Charge-to-discharge ratio* is the ratio of the time it takes to charge the device relative to the time it takes to discharge the device. For example, if a device takes 5 times longer to charge than to discharge, it has a charge-to-discharge ratio of 5:1.
- *Depth of discharge* (DoD) is the percentage of the battery capacity that is discharged during a cycle.
- *Memory effect*. If certain batteries are never fully discharged they 'remember' this and lose some of their capacity.

3 Energy storage plant components

Every energy storage facility is comprised of three primary components: storage medium, power conversion system (PCS), and balance of plant (BOP).

3.1 Storage medium

The storage medium is the 'energy reservoir' that retains the potential energy within a storage device. Storage media range from mechanical (PHES), chemical (BES) and electrical (SMES) potential energy.

3.2 Power conversion system

It is necessary to convert from alternating current (AC) to direct current (DC) and vice versa, for all storage devices except mechanical storage devices, e.g. PHES and CAES [3]. Consequently, a PCS is required that acts as a rectifier while the energy device is charged (AC to DC) and as an inverter when the device is discharged (DC to AC). The PCS also conditions the power during conversion to ensure that no damage is done to the storage device.

The customization of the PCS for individual storage systems has been identified as one of the primary sources of improvement for energy storage facilities, as each storage device operates differently during charging, standing and discharging [3].

The PCS usually costs from 33 to 50% of the entire storage facility. Development of PCSs has been slow due to the limited growth in distributed energy resources e.g. small-scale power generation technologies ranging from 3 to 10,000 kW [4].

3.3 Balance of plant

BOP comprises all additional works and ancillary components required to

- house the equipment
- control the environment of the storage facility
- provide the electrical connection between the PCS and the power grid

It is the most variable cost component within an energy storage device due to the various requirements for each facility. The BOP "typically includes electrical interconnections, surge protection devices, a support rack for the storage medium, the facility shelter and environmental control systems" [3]. The BOP may also include foundations, roadways, access, security equipment, electrical switchgear and metering equipment. Development activities including all paperwork, design, planning, safety, training and their costs are often included here.

4 Energy storage technologies

Energy storage devices by their nature are typically suitable for a very particular set of applications. This is primarily due to the potential power and storage capacities that can be obtained from the various devices. Therefore, in order to provide a fair comparison between the various energy storage technologies, they have been grouped together based on the size of power and storage capacity that can be obtained. Four categories have been created: devices large power (>50 MW) and storage (>100 MWh) capacities; devices with medium power (1–50 MW) and storage capacities (5–100 MWh); devices with medium power or storage capacities but not both; and finally, a section on energy storage systems.

The following energy storage technologies will be discussed under the respective groups: PHES, UPHES and CAES will be discussed together as they all have the potential for large power and storage capacities; BES and FBES will be discussed together as they have the potential for medium power and storage capacities, while SCES, FES and SMES will be grouped together as they all have either medium-scale power or storage capacities, and finally HESS, TESS and EVs will be discussed together as these are generally smaller energy storage systems. Before commencing it is worth noting which category each technology falls into. Only the technologies common by category will be compared against each other after they have been analysed. HESS, TESS and EVs have unique characteristics as these are energy systems, requiring a number of different technologies, which can be controlled differently. As energy systems transform from a fossil fuel production based on centralised production, to a renewable energy system, based on intermittent decentralised production, it is imperative that system flexibility is maximised. An ideal option to achieve this is by integrating the three primary sectors within any energy system: the electricity, heat and transport sectors. HESS, TESS and EVs provide unique opportunities to integrate these three sectors and hence increase the renewable energy penetrations feasible. As a result it is difficult to compare HESS, TESS and EVs to the other energy storage technologies directly as energy storage is only part of the purpose of those systems.

4.1 Pumped-hydroelectric energy storage

PHES is the most mature and largest capacity storage technique available. A pump and turbine have been combined in a single device optimised for this purpose. PHES consists of two large reservoirs located at different elevations and a number of pump turbine units (see Fig. 1). During off-peak electrical demand, water is pumped from the lower reservoir to the higher reservoir where it is stored until it is needed. When required (i.e. during peak electrical production) the water in the upper reservoir is released through the turbines, which are connected to generators that produce electricity. Therefore, during production a PHES facility operates similarly to a conventional hydroelectric system.

The efficiency of operational pumped storage facilities is in the region of 50–85% with more modern units at the upper end. However, variable speed machines are now being used to improve this. The efficiency is limited by the efficiency of the pump/turbine unit used in the facilities [2]. Until recently, PHES units have always used fresh water as the storage medium. However, in 1999 a PHES facility using seawater as the storage medium was constructed [6] (see Fig. 2); corrosion was

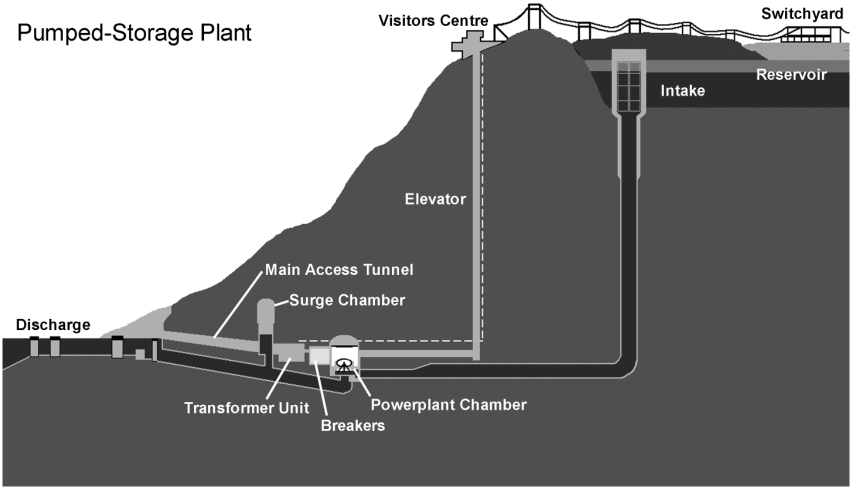


Figure 1: Pumped-hydroelectric energy storage layout [5].

Figure 2: Pumped-hydroelectric storage facility using seawater at Okinawa, Japan [6].

prevented by using paint and cathodic protection. A typical PHES facility has 300 m of hydraulic head (the vertical distance between the upper and lower reservoir). The power capacity (kW) is a function of the flow rate and the hydraulic head, while the energy stored (kWh) is a function of the reservoir volume and hydraulic head. To calculate the mass power output of a PHES facility, the following relationship can be used [7]:

$$P_{\mathrm{C}} = \rho g Q H n \tag{1}$$

where P_{C} is the power capacity in W, ρ the mass density of water in kg/m^3, g the acceleration due to gravity in m/s^2, Q the discharge through the turbines in m^3/s, H the effective head in m and n is the efficiency.

Also, the storage capacity of the PHES may be evaluated with the following equation [8]:

$$S_{\mathrm{C}} = V \rho g H n \tag{2}$$

where S_{C} is the storage capacity in megawatt-hours (MWh) and V is the volume of water that is drained and filled each day in m^3. It is evident that the power and storage capacities are both dependent on the head and the volume of the reservoirs. However, facilities should be designed with the greatest hydraulic head possible rather than largest upper reservoir possible. It is much cheaper to construct a facility with a large hydraulic head and small reservoirs, than to construct a facility of equal capacity with a small hydraulic head and large reservoirs because: less material needs to be removed to create the reservoirs required; smaller piping is necessary, hence, smaller boreholes during drilling; the pump turbine is physically smaller. Currently, there is over 90 GW in more than 240 PHES facilities in the world – roughly 3% of the world's global generating capacity. Individual facilities can store up to 15 GWh of electrical energy from in plant with power ratings from 30 to 4000 MW [2].

4.1.1 Applications of PHES

Similar to large storage capacities, PHES also has a fast reaction time, making it ideal for load levelling applications, where the plant can vary its effective load on the system from the full name plate rating in the positive direction (pumping) to the full name plate rating in the negative direction (generating) (see Fig. 3). Facilities can have a reaction time as short as 10 min or less from complete shutdown (or from full reversal of operation) to full power [3]. In addition, if kept on standby, full power can even be reached within 10–30 s.

Also, with the recent introduction of variable speed machines, PHES systems can now be used for frequency regulation in both pumping and generation modes (this has always been available in generating mode). This allows PHES units to absorb power in a more cost-effective manner that not only makes the facility more useful, but also improves the efficiency by approximately 3% [3] and extends the life of the facility. PHES can also be used for peak generation and black starts (start generating without access to a main frequency set by other units on the grid) due to its large power capacity and sufficient discharge time. Finally, PHES provides a load for base-load generating facilities during off-peak production, hence, cycling these units can be avoided which improves their lifetime as well as their efficiency.

4.1.2 Cost of PHES

Cost ranges from $600/kW [2] to upwards of $2000/kW [3], depending on a number of factors such as size, location and connection to the power grid.

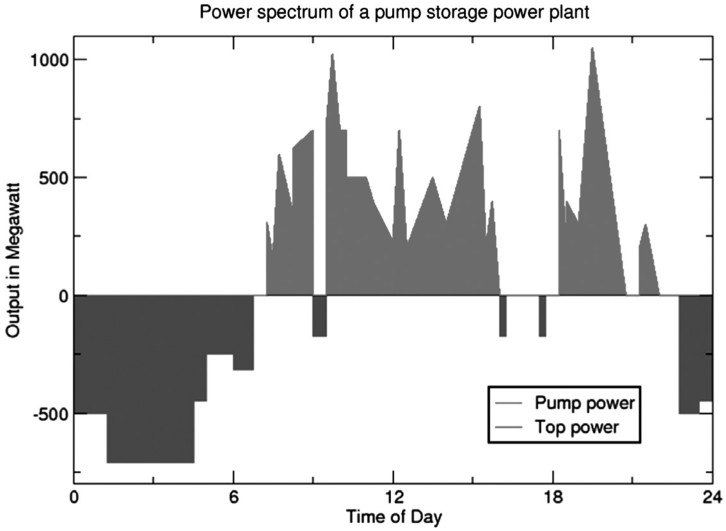


Figure 3: Output from a pumped-hydroelectric storage facility [5].

4.1.3 Disadvantages of PHES

A major disadvantage of PHES facility is its dependence on specific geological formations, because two large reservoirs with a sufficient hydraulic head between them must be located within close proximity to build a PHES system. As well as being rare, these geological formations normally exist in remote locations such as mountains, where construction is difficult and the power grid is not present, although large wind farm sites may provide a useful modern alternative. Finally, in order to make a PHES plant viable it must be constructed on a large scale. Although the cost per kWh of storage is relatively economical in comparison to other techniques, this results in a very high initial construction cost for the facility, therefore deterring investment in PHES, e.g. Bath County storage facility in the United States which has a power capacity of 2100 MW cost $1.7 billion in 1985.

4.1.4 Future of PHES

Currently, a lot of work is being carried out to upgrade old PHES facilities with new equipment such as variable speed devices which can increase capacity by 15–20% and efficiency by 5–10%. This is more desirable as energy storage capacity can be added without the high initial construction costs. Prospects of building new facilities are limited due to the “high development costs, long lead times and design limitations” [3]. However, a new concept that is showing a lot of theoretical potential is UPHES, discussed in the next section.

4.2 Underground pumped-hydroelectric energy storage

An UPHES facility has the same operating principle as PHES system: two reservoirs with a large hydraulic head between them. The only major difference between the two designs is the locations of their respective reservoirs. In conventional PHES, suitable geological formations must be identified to build the facility, as discussed earlier (see Section 5.1). However, UPHES facilities have been designed with the upper reservoir at ground level and the lower reservoir deep below the earth’s surface. The depth depends on the amount of hydraulic head required for the specific application (see Fig. 4).

4.2.1 Applications of UPHES

UPHES can provide the same services as PHES: load levelling, frequency regulation, and peak generation. However, as UPHES does not need to be built at a suitable geological formation, it can be constructed anywhere with an area large enough for the upper reservoir. Consequently, it can be placed in ideal locations to function with wind farms, the power grid, specific areas of electrical irregularities, etc. The flexibility of UPHES makes it a more attractive option for energy storage than conventional PHES, but its technical immaturity needs to be addressed.

4.2.2 Cost of UPHES

The capital cost of UPHES is the deciding factor for its future. As it operates in the same way as PHES, it is a very reliable and cost-effective storage technique with

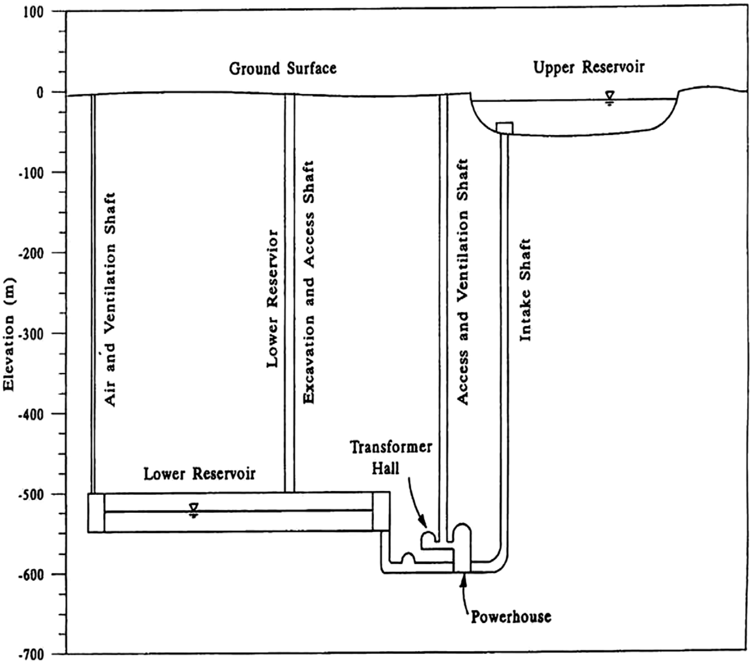


Figure 4: Proposed underground pumped-hydroelectric storage facility layout [7].

low maintenance costs. However, depending on the large capital costs involved, UPHES might not be a viable option as other technologies begin to develop larger storage capacities, e.g. flow batteries. Currently, no costs have been identified for UPHES, primarily due to the lack of facilities constructed. A number of possible cost-saving ideas have been put forward such as using old mines for the lower reservoir of the facility [7, 9]. Also, if something valuable can be removed to make the lower reservoir, it can be sold to make back some of the cost.

4.2.3 Disadvantages of UPHES

UPHES incorporates the same disadvantages as PHES (large-scale required, high capital costs, etc.), with one major exception. As stated previously (see Section 5.1), the most significant problem with PHES is its geological dependence. As the lower reservoir is obtained by drilling into the ground and the upper reservoir is at ground level, UPHES does not have such stringent geological dependences. The major disadvantage for UPHES is its commercial youth. To date there is very few, if any, UPHES facilities in operation. Therefore, it is very difficult to analyse and to trust the performance of this technology.

4.2.4 Future of UPHES

UPHES has a very bright future if cost-effective excavation techniques can be identified for its construction. Its relatively large-scale storage capacities, combined with its location independence, provide a storage technique with unique characteristics. However, as well as cost, a number of areas need to be investigated further in this area such as its design, power and storage capacities and environmental impact to prove it is a viable option.

4.3 Compressed air energy storage

A CAES facility consists of a power train motor that drives a compressor (to compress the air into the cavern), high pressure turbine (HPT), a low pressure turbine (LPT), and a generator (see Fig. 5).

In conventional gas turbines (GTs), 66% of the gas used is required to compress the air at the time of generation. Therefore, CAES pre-compresses the air using off-peak electrical power which is taken from the grid to drive a motor (rather than using gas from the GT plant) and stores it in large storage reservoirs. When the GT is producing electricity during peak hours, the compressed air is released from the storage facility and used in the GT cycle. As a result, instead of using expensive gas to compress the air, cheaper off-peak base-load electricity is used. However, when the air is released from the cavern it must be mixed with a small amount of gas before entering the turbine. If there was no gas added, the temperature and pressure of the air would be problematic. If the pressure using air alone was high enough to achieve a significant power output, the temperature of the air would be far too low for the materials and connections to tolerate [1]. The amount of gas

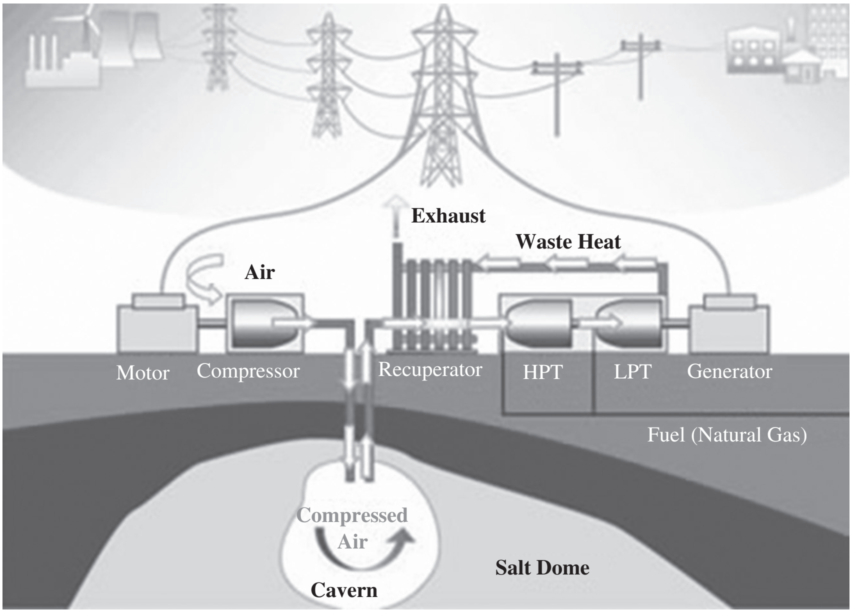


Figure 5: Compressed air energy storage facility [10].

required is so small that a GT working simultaneously with CAES can produce three times more electricity than a GT operating on its own, using the same amount of natural gas.

The reservoir can be man-made but this is expensive so CAES locations are usually decided by identifying natural geological formations that suit these facilities. These include salt-caverns, hard-rock caverns, depleted gas fields or an aquifer. Salt-caverns can be designed to suit specific requirements. Fresh water is pumped into the cavern and left until the salt dissolves and saturates the fresh water. The water is then returned to the surface and the process is repeated until the required volume cavern is created. This process is expensive and can take up to 2 years. The costs associated with hard-rock caverns are likely to be more than 50% higher. Finally, aquifers cannot store the air at high pressures and therefore have a relatively lower energy capacity.

CAES uses both electrical energy and natural gas so its efficiency is difficult to predict. It is estimated that the efficiency of the entire cycle is in the region of 64% [11] to 75% [3]. Typical plant capacities for CAES are in the region of 50–300 MW. The life of these facilities is proving to be far longer than existing GTs and the charge/discharge ratio is dependent on the size of the compressor used, as well as the size and pressure of the reservoir.

4.3.1 Applications of CAES

CAES is the only very large-scale storage technique other than PHES. CAES has a fast reaction time with plants usually able to go from 0 to 100% in less than 10 min, 10 to 100% in approximately 4 min and 50 to 100% in less than 15 s [2]. As a result, it is ideal for acting as a large sink for bulk energy supply and demand and also, it is able to undertake frequent start-ups and shutdowns. Furthermore, traditional GT suffer a 10% efficiency reduction from a 5°C rise in ambient temperatures due to a reduction in the air density. CAES use compressed air so they do not suffer from this effect. Also, traditional GTs suffer from excessive heat when operating on partial load, while CAES facilities do not. These flexibilities mean that CAES can be used for ancillary services such as frequency regulation, load following, and voltage control [3]. As a result, CAES has become a serious contender in the wind power energy storage market. A number of possibilities are being considered such as integrating a CAES facility with a number of wind farms within the same region. The excess off-peak power from these wind farms could be used to compress air for a CAES facility. *Iowa Association of Municipal Utilities* is currently planning a project of this nature [12].

4.3.2 Cost of CAES

The cost of CAES facilities are $425/kW [2] to $450/kW [3]. Maintenance is estimated between $3/kWh [13] and $10/kWh [14]. Costs are largely dependent on the reservoir construction. Overall, CAES facilities expect to have costs similar to or greater than conventional GT facilities. However, the energy cost is much lower for CAES systems.

4.3.3 Disadvantages of CAES

The major disadvantage of CAES facilities is their dependence on geographical location. It is difficult to identify underground reservoirs where a power plant can be constructed, is close to the electric grid, is able to retain compressed air and is large enough for the specific application. As a result, capital costs are generally very high for CAES systems. Also, CAES still uses a fossil fuel (gas) to generate electricity. Consequently, the emissions and safety regulations are similar to conventional GTs. Finally, only two CAES facilities currently exist, meaning it is still a technology of potential not experience.

4.3.4 Future of CAES

Reservoir developments are expected in the near future due to the increased use of natural gas storage facilities. The US and Europe are more likely to investigate this technology further as they possess acceptable geology for an underground reservoir (specifically salt domes). Due to the limited operational experience, CAES has been considered too risky by many utilities [14].

A number of CAES storage facilities have been planned for the future including:

- 25 MW CAES research facility with aquifer reservoir in Italy
- 3 × 100 MW CAES plant in Israel
- Norton Energy Storage LLC in America is planning a CAES with a limestone mine acting as the reservoir. The first of four phases is expected to produce between 200 and 480 MW at a cost of $50 to $480 million. The final plant output is planned to be 2500 MW.

Finally, proposals have also been put forward for a number of similar technologies such as micro-CAES and thermal and compressed air storage (TACAS). However, both are in the early stages of development and their future impact is not decisive. Although Joe Pinkerton, CEO of *Active Power*, declared that TACAS "is the first true minute-for-minute alternative to batteries for UPS industry" [3].

4.4 Battery energy storage

There are three important types of large-scale BES. These are: lead-acid (LA); nickel-cadmium (NiCd); sodium-sulphur (NaS). These operate in the same way as conventional batteries, except on a large scale, i.e. two electrodes are immersed in an electrolyte, which allows a chemical reaction to take place so current can be produced when required.

4.4.1 LA battery

This is the most common energy storage device in use at present. Its success is due to its maturity (research has been ongoing for an estimated 140 years), relatively low cost, long lifespan, fast response, and low self-discharge rate. These batteries are can be used for both short-term applications (seconds) and long-term applications (up to 8 h). There are two types of LA batteries; flooded lead-acid (FLA) and valve-regulated lead-acid (VRLA). FLA batteries are made up of two electrodes that are constructed using lead plates which are immersed in a mixture of water (65%) and sulphuric acid (35%) (see Fig. 6). VRLA batteries have the same operating principle as FLA batteries, but they are sealed with a pressure-regulating valve. This eliminates air from entering the cells and also prevents venting of the hydrogen. VRLA batteries have lower maintenance costs, weigh less and occupy less space. However, these advantages are coupled with higher initial costs and shorter lifetime.

Both the power and energy capacities of LA batteries are based on the size and geometry of the electrodes. The power capacity can be increased by increasing the surface area for each electrode, which means greater quantities of thinner electrode plates in the battery. However, to increase the storage capacity of the battery, the mass of each electrode must be increased, which means fewer and thicker plates. Consequently, a compromise must be met for each application. LA batteries can respond within milliseconds at full power. The average DC–DC efficiency of a LA battery is 75–85% during normal operation, with a life of approximately 5 years or 250–1000 charge/discharge cycles, depending on the depth of discharge [3].

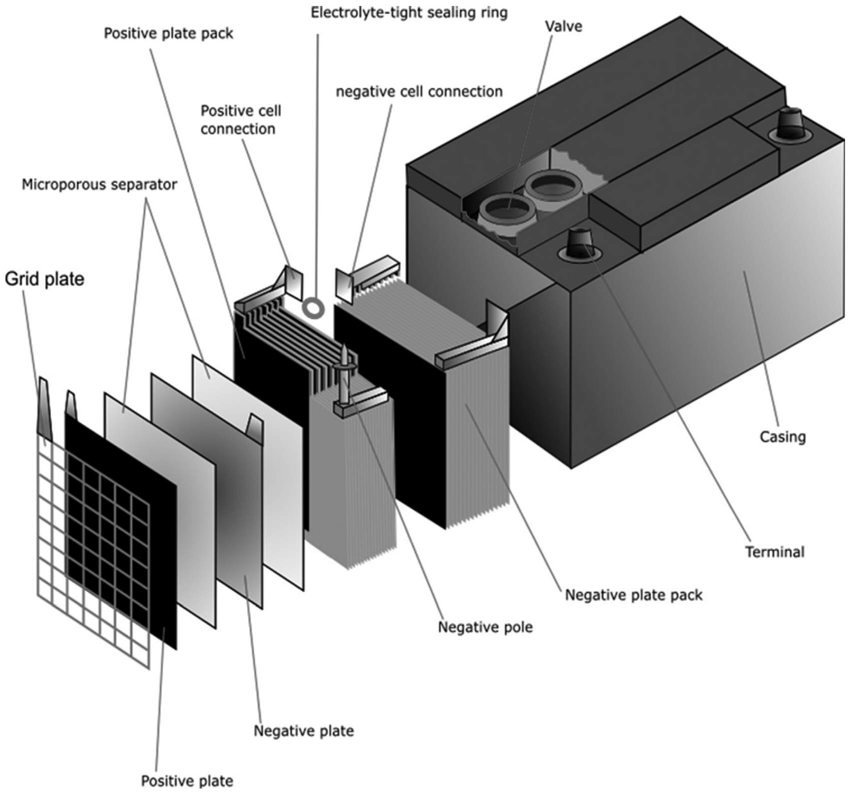


Figure 6: Lead acid battery [15].

4.4.1.1 Applications of LA battery

FLA batteries have two primary applications [3]:

1. Starting and ignition, short bursts of strong power e.g. car engine batteries
2. Deep cycle, low steady power over a long time

VRLA batteries are very popular for backup power, standby power supplies in telecommunications and also for UPS systems. A number of LA storage facilities are in operation today as can be seen in Table 1.

4.4.1.2 Cost of LA battery

Costs for LA battery technology have been stated as $200/kW to $300/kW [2], but also in the region of $580/kW [3]. Looking at Table 1, the cost variation is evident.

4.4.1.3 Disadvantages of LA battery

LA batteries are extremely sensitive to their environments. The typical operating temperature for a LA battery is roughly 27°C, but a change in temperature of 5°C or more can cut the life of the battery by 50%. However, if the DoD exceeds this, the cycle life of the battery will also be reduced. Finally, a typical charge-to-discharge ratio of a LA battery is 5:1. At faster rates of charge, the cell will be damaged.

Table 1: Largest LA and VRLA batteries installed worldwide [2].

				Battery system alone		Total cost of the storage system*	
Plant	Year of installation	Rated Energy (MWh)	Rate Power (MW)	Cost in $1995 ($/kWh)	Cost in $1995 ($/kWh)	Cost in $1995 ($/kW)	Cost in $1995 ($/kW)
CHINO California	1988	40	10	201	805	456	1823
HELCO Hawaii (VRLA)	1993	15	10	304	456	777	1166
PREPA Puerto Rico	1994	14	20	341	239	1574	1102
BEWAG Germany	1986	8.5	8.5	707	707	n/a	n/a
VERNON California (VRLA)	1995	4.5	3	305	458	944	1416

*Includes power conditioning system and balance-of-payment.

4.4.1.4 Future of LA battery

Due to the low cost and maturity of the LA battery it will probably always be useful for specific applications. The international *Advanced Lead-Acid Battery Consortium* is also developing a technique to significantly improve storage capacity and also recharge the battery in only a few minutes, instead of the current hours [2]. However, the requirements of new large-scale storage devices would significantly limit the life of a LA battery. Consequently, a lot of research has been directed towards other areas. Therefore, it is unlikely that LA batteries will be competing for future large-scale multi-MW applications.

4.4.2 NiCd battery

A NiCd battery is made up of a positive with nickel oxyhydroxide as the active material and a negative electrode composed of metallic cadmium. These are separated by a nylon divider (see Fig. 7). The electrolyte, which undergoes no significant changes during operation, is aqueous potassium hydroxide. During discharge, the nickel oxyhydroxide combines with water and produces nickel hydroxide and a hydroxide ion. Cadmium hydroxide is produced at the negative electrode. To charge the battery the process can be reversed. However, during charging, oxygen can be produced at the positive electrode and hydrogen can be produced at the negative electrode. As a result some venting and water addition is required, but much less than required for a LA battery.

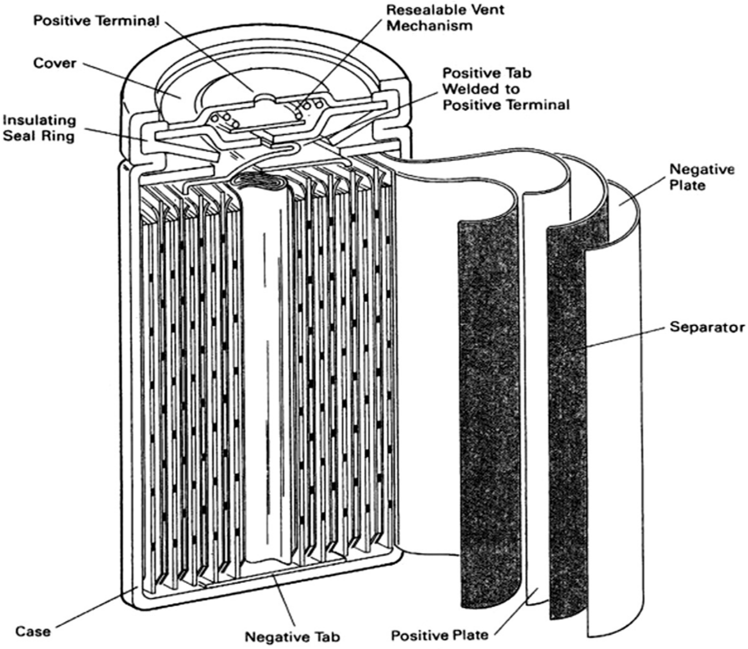


Figure 7: Nickel-cadmium battery [16].

There are two NiCd battery designs: vented and sealed. Sealed NiCd batteries are the common, everyday rechargeable batteries used in a remote control, lamp, etc. No gases are released from these batteries, unless a fault occurs. Vented NiCd batteries have the same operating principles as sealed ones, but gas is released if overcharging or rapid discharging occurs. The oxygen and hydrogen are released through a low pressure release valve making the battery safer, lighter, more economical, and more robust than sealed NiCd batteries.

The DC–DC efficiency of a NiCd battery is 60–70% during normal operation although the life of these batteries is relatively high at 10–15 years, depending on the application. NiCd batteries with a pocket-plate design have a life of 1000 charge/discharge cycles, and batteries with sintered electrodes have a life of 3500 charge/discharge cycles. NiCd batteries can respond at full power within milliseconds. At small DoD rates (approximately 10%) NiCd batteries have a much longer cycle life (50,000 cycles) than other batteries such as LA batteries. They can also operate over a much wider temperature range than LA batteries, with some able to withstand occasional temperatures as high as 50°C.

4.4.2.1 Applications of NiCd battery

Sealed NiCd batteries are used commonly in commercial electronic products such as a remote control, where light weight, portability, and rechargeable power are important. Vented NiCd batteries are used in aircraft and diesel engine starters, where large energy per weight and volume are critical [3]. NiCd batteries are ideal for protecting power quality against voltage sags and providing standby power in harsh conditions. Recently, NiCd batteries have become popular as storage for solar generation because they can withstand high temperatures. However, they do not perform well during peak shaving applications, and consequently are generally avoided for energy management systems.

4.4.2.2 Cost of NiCd battery

NiCd batteries cost more than LA batteries at $600/kW [3]. However, despite the slightly higher initial cost, NiCd batteries have much lower maintenance costs due to their environmental tolerance.

4.4.2.3 Disadvantages of NiCd battery

Like LA batteries, the life of NiCd batteries can be greatly reduced due to the DoD and rapid charge/discharge cycles. However, NiCd batteries suffer from 'memory' effects and also lose more energy during due to self-discharge standby than LA batteries, with an estimated 2–5% of their charge lost per month at room temperature in comparison to 1% per month for LA batteries [3]. Also, the environmental effects of NiCd batteries have become a widespread concern in recent years as cadmium is a toxic material. This creates a number of problems for disposing of the batteries.

4.4.2.4 Future of NiCd battery

It is predicted that NiCd batteries will remain popular within their current market areas, but like LA batteries, it is unlikely that they will be used for future large-scale projects. Although just to note, a 40 MW NiCd storage facility was constructed in Alaska; comprising of 13,760 cells at a cost of $35M [2]. The cold temperatures experienced were the primary driving force behind the use NiCd as a storage medium. NiCd will probably remain more expensive than LA batteries, but they do provide better power delivery. However, due to the toxicity of cadmium, standards and regulations for NiCd batteries will continue to rise.

4.4.3 NaS battery

NaS batteries have three times the energy density of LA, a longer life span, and lower maintenance. These batteries are made up of a cylindrical electrochemical cell that contains a molten-sodium negative electrode and a molten-sulphur positive electrode. The electrolyte used is solid β-alumina. During discharging, sodium ions pass through the β-alumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulphide (see Fig. 8). During charging, the reaction is reversed so that the sodium polysulphide decomposes, and the sodium ions are converted to sodium at the positive electrode. In order to keep the sodium and sulphur molten in the battery, and to obtain adequate conductivity in the electrolyte, they are housed in a thermally insulated enclosure that must keep it above 270°C, usually at 320–340°C.

A typical NaS module is 50 kW at 360 kWh or 50 kW at 430 kWh. The average round-trip energy efficiency of a NaS battery is 86% [2] to 89% [3]. The cycle life is much better than for LA or NiCd batteries. At 100% DoD, the NaS batteries can last approximately 2500 cycles. As with other batteries, this increases as the DoD decreases; at 90% DoD the unit can cycle 4500 times and at 20% DoD 40,000 times [3].

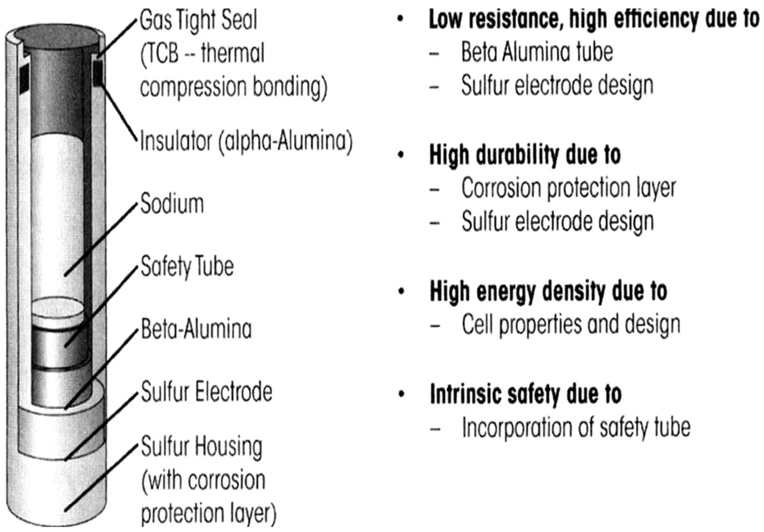


Figure 8: Sodium-sulphur battery [3].

One of the greatest characteristics of NaS batteries is its ability to provide power in a single, continuous discharge or else in shorter larger pulses (up to five times higher than the continuous rating). It is also capable of pulsing in the middle of a long-term discharge. This flexibility makes it very advantageous for numerous applications such as energy management and power quality. NaS batteries have also been used for deferring transmission upgrades. Currently, NaS batteries cost $810/kW, but it is only a recently commercialised product. This cost is likely to be reduced as production increases, with some predicting reductions upwards of 33% [3]. The major disadvantage of NaS batteries is retaining the device at elevated temperatures above 270°C. It is not only energy consuming, but it also brings with it problems such as thermal management and safety regulations [17]. Also, due to harsh chemical environments, the insulators can be a problem as they slowly become conducting and self-discharge the battery.

A 6 MW, 8 h unit has been built by *Tokyo Electric Power Company* (TEPCO) and *NGK Insulators, Ltd.* (NGK), in Tokyo, Japan with an overall plant efficiency of 75% and is thus far proving to be a success (see Fig. 9). The materials required to create a NaS battery are inexpensive and abundant, and 99% of the battery is recyclable. The NaS battery has the potential to be used on a MW scale by combining modules. Combining this with its functionality to mitigate power disturbances, NaS batteries could be a viable option for smoothing the output from wind turbines into the power grid [3]. *American Electric Power* is planning to incorporate a 6 MW NaS battery with a wind farm for a 2-year demonstration [18, 19]. The size of the wind farm has yet to be announced but the results from this will be vital for the future of the NaS battery.

4.5 Flow battery energy storage

There are three primary types of FBES: vanadium redox (VR); polysulphide bromide (PSB); zinc-bromine (ZnBr). They all operate in a similar fashion: two charged electrolytes are pumped to the cell stack where a chemical reaction occurs, allowing current to be obtained from the device when required. The operation of each will be discussed in more detail during the analysis.

Figure 9: 6 MW, 8 h Sodium-sulphur energy storage facility in Tokyo, Japan [2].

4.5.1 VR flow battery

A VR battery is made up of a cell stack, electrolyte tank system, control system and a PCS (see Fig. 10). These batteries store energy by interconnecting two forms of vanadium ions in a sulphuric acid electrolyte at each electrode; with V^{2+}/ V^{3+} in the negative electrode, and V^{4+}/ V^{5+} in the positive electrode. The size of the cell stack determines the power capacity (kW) whereas the volume of electrolyte (size of tanks) indicates the energy capacity (kWh) of the battery.

As the battery discharges, the two electrolytes flow from their separate tanks to the cell stack where H^+ ions are passed between the two electrolytes through the permeable membrane. This process induces self-separation within the solution thus changing the ionic form of the vanadium as the potential energy is converted to electrical energy. During recharge this process is reversed. VR batteries operate at normal temperature with an efficiency as high as 85% [2, 3]. As the same chemical reaction occurs for charging and discharging, the charge/discharge ratio is 1:1. The VR battery has a fast response, from charge to discharge in 0.001 s and also a high overload capacity with some claiming it can reach twice its rated capacity for several minutes [2]. VR batteries can operate for 10,000 cycles giving them an estimated life of 7–15 years depending on the application. Unlike conventional batteries they can be fully discharged without any decline in performance [21]. At the end of its life (10,000 cycles), only the cell stack needs to be replaced as the electrolyte has an indefinite life and thus can be reused. VR batteries have been designed as modules so they can be constructed on-site.

4.5.1.1 Applications of VR flow battery

As the power and energy capacities are decoupled, the VR flow battery is a very versatile device in terms of energy storage. It can be used for every energy storage requirement including UPS, load levelling, peak shaving, telecommunications, electric utilities and integrating renewable resources. Although the versatility of flow batteries makes it extremely useful for a lot of applications, there are a number of competing devices within each area that perform better for their specific application. Consequently, although capable of performing for numerous applications,

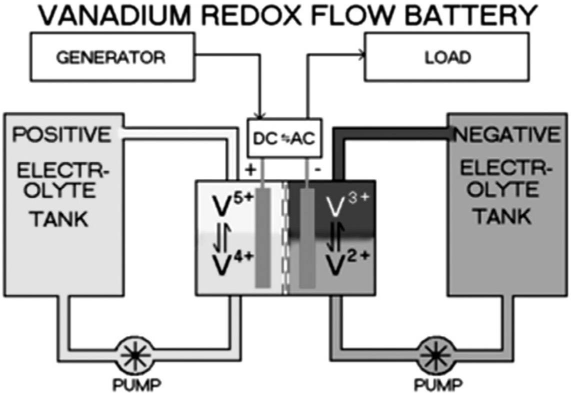


Figure 10: Vanadium redox flow battery [20].

VR batteries are only considered where versatility is important, such as the integration of renewable resources.

4.5.1.2 Cost of VR flow battery

There are two costs associated with flow batteries: the power cost (kW), and the energy cost (kWh), as they are independent of each other. The power cost for VR batteries is $1828/kW, and the energy cost is $300/kWh to $1000/kWh, depending on system design [3].

4.5.1.3 Disadvantages of VR flow battery

VR batteries have the lowest power density and require the most cells (each cell has a voltage of 1.2 V) in order to obtain the same power output as other flow batteries. For smaller-scale energy applications, VR batteries are very complicated in relation to conventional batteries, as they require much more parts (such as pumps, sensors, control units) while providing similar characteristics. Consequently, when deciding between a flow battery and a conventional battery, a decision must be made between a simple but constrained device (conventional battery), and a complex but versatile device (flow battery).

4.5.1.4 Future of VR flow battery

VR batteries have a lot of potential due to their unique versatility, specifically their MW power and storage capacity potential. However, the commercial immaturity of VR batteries needs to be changed to prove it is a viable option in the future.

4.5.2 PSB flow battery

PSB batteries operate very similarly to VR batteries. The unit is made up of the same components; a cell stack, electrolyte tank system, control system and a PCS (see Fig. 11). The electrolytes used within PSB flow batteries are sodium bromide as the positive electrolyte, and sodium polysulphide as the negative electrolyte.

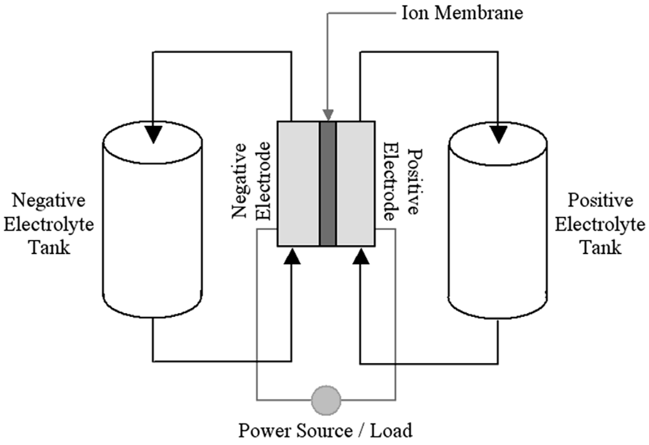


Figure 11: Polysulphide bromide flow battery [3].

During discharge, the two electrolytes flow from their tanks to the cell where the reaction takes place at a polymer membrane that allows sodium ions to pass through. Like VR batteries, self-separation occurs during the discharge process and as before, to recharge the battery this process is simply reversed. The voltage across each cell is approximately 1.5 V.

PSB batteries operate between 20 and 40°C, but a wider range can be used if a plate cooler is used in the system. The efficiency of PSB flow batteries approaches 75% according to [2, 3]. As with VR batteries, the discharge ratio is 1:1, since the same chemical reaction is taking place during charging and discharging. The life expectancy is estimated at 2000 cycles but once again, this is very dependent on the application. As with VR batteries the power and energy capacities are decoupled in PSB batteries.

4.5.2.1 Applications of PSB flow battery

PSB flow batteries can be used for all energy storage requirements including load levelling, peak shaving, and integration of renewable resources. However, PSB batteries have a very fast response time; it can react within 20 ms if electrolyte is retained charged in the stacks (of cells). Under normal conditions, PSB batteries can charge or discharge power within 0.1 s [2]. Therefore, PSB batteries are particularly useful for frequency response and voltage control.

4.5.2.2 Cost PSB flow battery

The power capacity cost of PSB batteries is $1094/kW and the energy capacity cost is $185/kWh [3].

4.5.2.3 Disadvantages PSB flow battery

During the chemical reaction small quantities of bromine, hydrogen, and sodium sulphate crystals are produced. Consequently, biweekly maintenance is required to remove the NaS by-products. Also, two companies designed and planned to build PSB flow batteries. *Innogy's Little Barford Power Station* in the UK wanted to use a 24,000 cell 15 MW 120 MWh PSB battery, to support a 680 MW combined-cycle gas turbine plant. Tennessee Valley Authority (TVA) in Columbus wanted a 12 MW, 120 MWh to avoid upgrading the network. However, both facilities have been cancelled with no known explanation.

4.5.2.4 Future PSB flow battery

Like the VR battery, PSB batteries can scale into the MW region and therefore must have a future within energy storage. However, until a commercial demonstration succeeds, the future of PSB batteries will remain doubtful.

4.5.3 Zinc-bromine (ZnBr) flow battery

These flow batteries are slightly different to VR and PSB flow batteries. Although they contain the same components: a cell stack, electrolyte tank system, control system, and a PCS (see Fig. 12) they do not operate in the same way.

During charging the electrolytes of zinc and bromine ions (that only differ in their concentration of elemental bromine) flow to the cell stack. The electrolytes

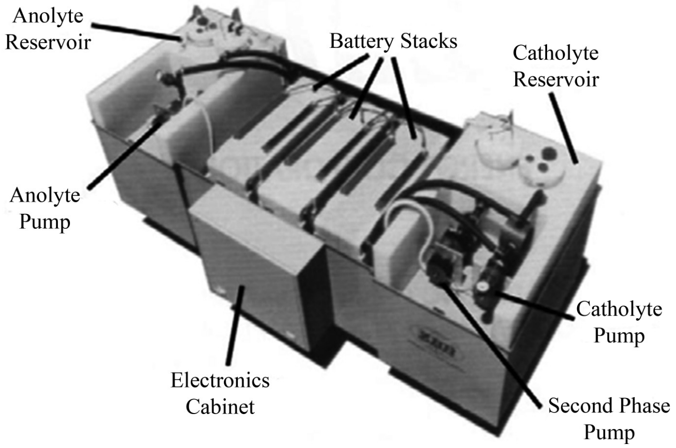


Figure 12: Zinc-bromine battery [22].

are separated by a microporous membrane. Unlike VR and PSB flow batteries, the electrodes in a ZnBr flow battery act as substrates to the reaction. As the reaction occurs, zinc is electroplated on the negative electrode and bromine is evolved at the positive electrode, which is somewhat similar to conventional battery operation. An agent is added to the electrolyte to reduce the reactivity of the elemental bromine. This reduces the self-discharge of the bromine and improves the safety of the entire system [22]. During discharge the reaction is reversed; zinc dissolves from the negative electrode and bromide is formed at the positive electrode. ZnBr batteries can operate in a temperature range of 20–50°C. Heat must be removed by a small chiller if necessary. No electrolyte is discharged from the facility during operation and hence the electrolyte has an indefinite life. The membrane however, suffers from slight degradation during the operation, giving the system a cycle life of approximately 2000 cycles. The ZnBr battery can be 100% discharged without any detrimental consequences and suffers from no memory effect. The efficiency of the system is about 75% [2] or 80% [3]. Once again, as the same reaction occurs during charging and discharging, the charge/discharge ratio is 1:1, although a slower rate is often used to increase efficiency [3]. Finally, the ZnBr flow battery has the highest energy density of all the flow batteries, with a cell voltage of 1.8 V.

4.5.3.1 Applications of ZnBr flow battery

The building block for ZnBr flow batteries is a 25 kW, 50 kWh module constructed from three 60-cell battery stacks in parallel, each with an active cell area of 2500 cm^2 [22]. ZnBr batteries also have a high energy density of 75–85 Wh/kg. As a result, the ZnBr batteries are relatively small and light in comparison to other conventional and flow batteries such as LA, VR and PSB. Consequently, ZnBr is currently aiming at the renewable energy backup market. It is capable of smoothing the output fluctuations from a wind farm [2], or a solar panel [22], as well as providing frequency control. Installations currently completed have used ZnBr flow batteries for UPS, load management and supporting microturbines, solar generators, substations and T&D grids [2].

4.5.3.2 Cost of ZnBr flow battery

The power capacity cost is $639/kW and the energy capacity cost is $400/kWh [3].

4.5.3.3 Disadvantages of ZnBr flow battery

It is difficult to increase the power and storage capacities into the large MW ranges as the modules cannot be linked hydraulically, hence the electrolyte is isolated within each module. Modules can be linked electrically though and plans indicate that systems up to 1.5 MW are possible. As stated, the membrane suffers from slight degradation during the reaction so it must be replaced at the end of the batteries life (2000 cycles).

4.5.3.4 Future of ZnBr flow battery

The future of ZnBr batteries is currently aimed at the renewable energy market. *Apollo Energy Corporation* plan to develop a 1.5 MW ZnBr battery to back up a 20 MW wind farm for several minutes. They hope to keep the wind farm operational for an additional 200+ h a year [2]. The results from this will be very decisive for the future of ZnBr flow batteries.

4.6 Flywheel energy storage

A FES device is made up of a central shaft that holds a rotor and a flywheel. This central shaft rotates on two magnetic bearings to reduce friction (see Fig. 13). These are all

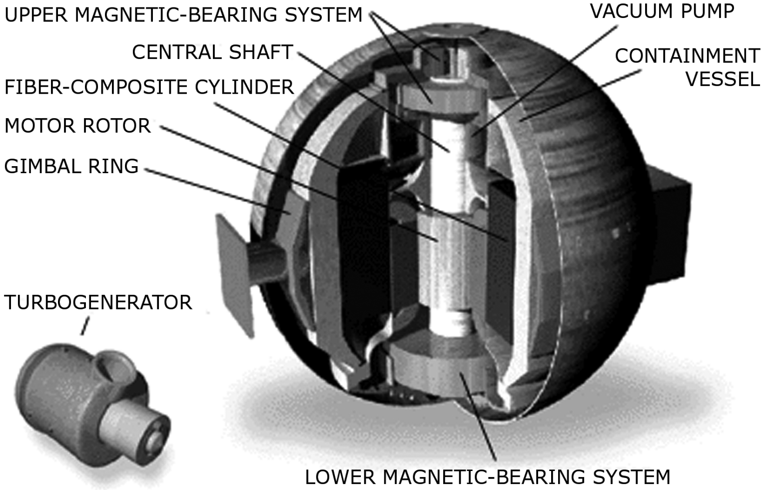


Figure 13: Flywheel energy storage device [23].

contained within a vacuum to reduce aerodynamic drag losses. Flywheels store energy by accelerating the rotor/flywheel to a very high speed and maintaining the energy in the system as kinetic energy. Flywheels release energy by reversing the charging process so that the motor is then used as a generator. As the flywheel discharges, the rotor/flywheel slows down until eventually coming to a complete stop.

The rotor dictates the amount of energy that the flywheel is capable of storing. Flywheels store power in direct relation to the mass of the rotor, but to the square of its surface speed. Consequently, the most efficient way to store energy in a flywheel is to make it spin faster, not by making it heavier. The energy density within a flywheel is defined as the energy per unit mass:

$$E_{\mathrm{f}} = \frac{I\omega^2}{2} = \frac{m_{\mathrm{f}} r^2 \omega^2}{2} \tag{3}$$

where E_{f} is the total kinetic energy in J, I the moment of inertia in kg/m^2, ω the angular velocity of the flywheel in rad/s, m_{f} the mass of the flywheel in kg and r is the radius in m.

The power and energy capacities are decoupled in flywheels. In order to obtain the required power capacity, you must optimise the motor/generator and the power electronics. These systems, referred to as 'low speed flywheels', usually have relatively low rotational speeds, approximately 10,000 rpm and a heavy rotor made form steel. They can provide up to 1650 kW, but for a very short time, up to 120 s.

To optimise the storage capacities of a flywheel, the rotor speed must be increased. These systems, referred to as 'high speed flywheels', spin on a lighter rotor at much higher speeds, with some prototype composite flywheels claiming to reach speeds in excess of 100,000 rpm. However, the fastest flywheels commercially available spin at about 80,000 rpm. They can provide energy up to an hour, but with a maximum power of 750 kW.

Over the past number of years, the efficiency of flywheels has improved up to 80% [3], although some sources claim that it can be as high as 90% [1]. As it is a mechanical device, the charge-to-discharge ratio is 1:1.

4.6.1 Applications of FES

Flywheels have an extremely fast dynamic response, a long life, require little maintenance, and are environmentally friendly. They have a predicted lifetime of approximately 20 years or tens of thousands of cycles. As the storage medium used in flywheels is mechanical, the unit can be discharged repeatedly and fully without any damage to the device. Consequently, flywheels are used for power quality enhancements such as uninterruptible power supply (UPS), capturing waste energy that is very useful in EV applications and finally, to dampen frequency variation, making FES very useful to smooth the irregular electrical output from wind turbines.

4.6.2 Cost of FES

At present, FES systems cost between \$200/kWh to \$300/kWh for low speed flywheels, and \$25,000/kWh for high speed flywheels [2]. The large cost for high speed flywheels is typical for a technology in the early stages of development.

Battery technology such as the LA battery is the main competitor for FES. These have similar characteristics to FES devices, and usually cost 33% less [3]. However, as mentioned previously (see Section 3.7.1), FES have a longer life span, require lower maintenance, have a faster charge/discharge, take up less space and have fewer environmental risks [2].

4.6.3 Disadvantages of FES

As flywheels are optimised for power or storage capacities, the needs of one application can often make the design poorly suited for the other. Consequently, low speed flywheels may be able to provide high power capacities but only for very short time period, and high speed flywheels the opposite. Also, as flywheels are kept in a vacuum during operation, it is difficult to transfer heat out of the system, so a cooling system is usually integrated with the FES device. Finally, FES devices also suffer from the idling losses: when flywheels are spinning on standby, energy is lost due to external forces such as friction or magnetic forces. As a result, flywheels need to be pushed to maintain its speed. However, these idling losses are usually less than 2%.

4.6.4 Future of FES

Low maintenance costs and the ability to survive in harsh conditions are the core strengths for the future of flywheels. Flywheels currently represent 20% of the $1-billion energy storage market for UPS. Due to its size and cycling capabilities, FES could establish even more within this market if consumers see beyond the larger initial investment. As flywheels require a preference between optimization of power or storage capacity, it is unlikely to be considered a viable option as a sole storage provider for power generation applications. Therefore, FES needs to extend into applications such as regenerative energy and frequency regulation where it is not currently fashionable if it is to have a future [3].

4.7 Supercapacitor energy storage

Capacitors consist of two parallel plates that are separated by a dielectric insulator (see Fig. 14). The plates hold opposite charges which induce an electric field, in which energy can be stored. The energy within a capacitor is given by:

$$E = \frac{CV}{2} \tag{4}$$

where E is the energy stored within the capacitor (in J), V the voltage applied, and C is the capacitance found from [1]:

$$C = \frac{A\varepsilon_r\varepsilon_0}{d} \tag{5}$$

where A is the area of the parallel plates, d the distance between the two plates, ε_r the relative permittivity or dielectric constant, and ε_0 is the permittivity of free

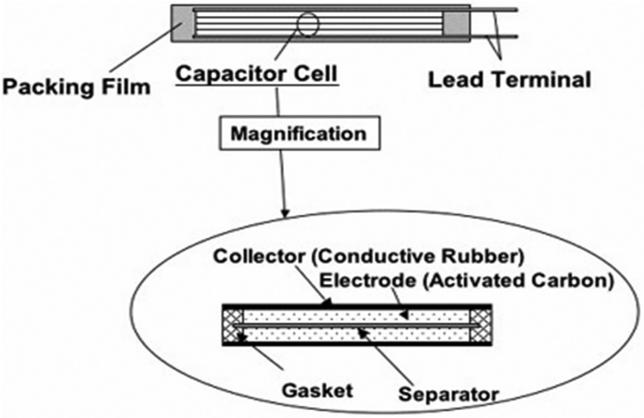


Figure 14: Supercapacitor energy storage device [24].

space (8.854×10^{-12} F/m). Therefore, to increase the energy stored within a capacitor, the voltage or capacitance must be increased. The voltage is limited by the maximum energy field strength (after this the dielectric breaks down and starts conducting), and the capacitance depends on the dielectric constant of the material used.

Supercapacitors are created by using thin film polymers for the dielectric layer and carbon nanotube electrodes. They use polarised liquid layers between conducting ionic electrolyte and a conducting electrode to increase the capacitance. They can be connected in series or in parallel. SCES systems usually have energy densities of 20–70 MJ/m^3, with an efficiency of 95% [2].

4.7.1 Applications of SCES

The main attraction of SCES is its fast charge and discharge, combined with its extremely long life of approximately 1×10^6 cycles. This makes it a very attractive replacement for a number of small-scale (<250 kW) power quality applications. In comparison to batteries, supercapacitors have a longer life, do not suffer from memory effect, show minimal degradation due to deep discharge, do not heat up, and produce no hazardous substances [1]. As a result, although the energy density is smaller, SCES is a very attractive option for some applications such as hybrid cars, cellular phones, and load levelling tasks. SCES is primarily used where pulsed power is needed in the millisecond to second time range, with discharge times up to 1 min [2].

4.7.2 Cost of SCES

SCES costs approximately \$12,960/kWh [2] to \$28,000/kWh [1]. Therefore, large-scale applications are not economical using SCES.

4.7.3 Disadvantages of SCES

SCES has a very low energy storage density leading to very high capital costs for large-scale applications. Also, they are heavier and bulkier than conventional batteries.

4.7.4 Future of SCES

Despite the small energy storage densities on offer, the exceptional life and cycling capabilities, fast response and good power capacity (up to 1 MW) of supercapacitors means that they will always be useful for specific applications. However, it is unlikely that SCES will be used as a sole energy storage device. One long-term possibility involves combining SCES with a battery-based storage system. SCES could smooth power fluctuations, and the battery provides the storage capacity necessary for longer interruptions. However, other technologies (such as flow batteries) are more likely to be developed for such applications. As a result, the future of SCES is likely to remain within specific areas that require a lot of power, very fast, for very short periods.

4.8 Superconducting magnetic energy storage

A SMES device is made up of a superconducting coil, a power conditioning system, a refrigerator and a vacuum to keep the coil at low temperature (see Fig. 15).

Energy is stored in the magnetic field created by the flow of DC in the coil wire. In general, when current is passed through a wire, energy is dissipated as heat due to the resistance of the wire. However, if the wire used is made from a superconducting material such as lead, mercury or vanadium, zero resistance occurs, so energy can be stored with practically no losses. In order to obtain this superconducting state within a material, it must be kept at a very low temperature. There are two types of superconductors: low-temperature superconductors that must be cooled to between 0 and 7.2 K, and high-temperature superconductors that have a temperature range of 10–150 K, but are usually in the 100 ± 10 K region. The energy stored within the coil (in J), E_C, can be obtained from [1]:

$$E = \frac{LI}{2} \tag{6}$$

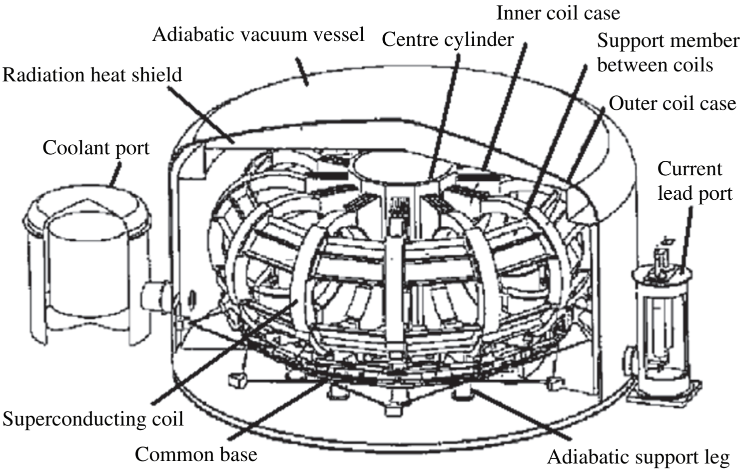


Figure 15: Superconducting magnetic energy storage device [2].

where L is the inductance of the coil, and I is the current passing through it. Therefore, material properties are extremely important as temperature, magnetic field, and current density are pivotal factors in the design of SMES. The overall efficiency of SMES is in the region of 90% [13] to 99% [3]. SMES has very fast discharge times, but only for very short periods of time, usually taking less than 1 min for a full discharge. Discharging is possible in milliseconds if it is economical to have a PCS that is capable of supporting this. Storage capacities for SMES can be anything up to 2 MW, although its cycling capability is its main attraction. SMES devices can run for thousands of charge/discharge cycles without any degradation to the magnet, giving it a life of 20+ years.

4.8.1 Applications of SMES

Due to the high power capacity and instantaneous discharge rates of SMES, it is ideal for the industrial power quality market. It protects equipment from rapid momentary voltage sags, and it stabilises fluctuations within the entire network caused by sudden changes in consumer demand levels, lightening strikes or operation switches. As a result, SMES is a very useful network upgrade solution with some sources claiming that it can improve the capacity of a local network by up to 15% [3]. However, due to high energy consumption of the refrigeration system, SMES is unsuitable for daily cycling applications such as peak reduction, renewable applications, and generation and transmission deferral [2].

4.8.2 Cost of SMES

SMES cost approximately \$300/kW [2] to \$509/kW [3]. It is worth noting that it is difficult to compare the cost of SMES to other storage devices due to its scales and purpose. In practical terms SMES should be compared to other network upgrade solutions where it is often very competitive or even less costly. Finally, the cost of storing electricity within a superconductor is expected to decline by almost 30% which could make SMES an even more attractive option for network improvements [3].

4.8.3 Disadvantages of SMES

The most significant drawback of SMES is its sensitivity to temperature. As discussed the coil must be maintained at an extremely low temperature in order to behave like a superconductor. However, a very small change in temperature can cause the coil to become unstable and lose energy. Also, the refrigeration can cause parasitic losses within the system. Finally, although the rapid discharge rates provide some unique applications for SMES, it also limits its applications significantly. As a result, other multifunctional storage devices such as batteries are usually more attractive.

4.8.4 Future of SMES

Immediate focus will be in developing small SMES devices in the range of 1–10 MW for the power quality market which has foreseeable commercial potential. A lot of work is being carried out to reduce the capital and operating costs of high-temperature SMES devices, as it is expected to be the commercial superconductor of choice once manufacturing processes are more mature, primarily due to cheaper cooling. There is a lot of market potential for SMES due to its unique application characteristics, primarily in transmission upgrades and industrial power quality [3]. However, one of the greatest concerns for SMES is its reliability over a long period of time.

4.9 Hydrogen energy storage system

HESS is the first of the three energy storage systems discussed in this chapter. HESS is the one of the most immature but also one of the most promising energy storage techniques available. As an energy storage system, HESS acts as a bridge between all three major sectors of an energy system: the electricity, heat and transport sectors. It is the only energy storage system that allows this level of interaction between these sectors and hence it is becoming a very attractive option for integrating large quantities of intermittent wind energy. There are three stages in HESS: create hydrogen; store hydrogen; use hydrogen (for required application).

4.9.1 Hydrogen production

There are three primary techniques to produce hydrogen: extraction from fossil fuels; reacting steam with methane; electricity (electrolysis). However, as producing hydrogen from fossil fuels is four times more expensive than using the fuel itself, and reacting steam with methane produces pollutants, electrolysis has become the most promising technique for hydrogen production going forward.

An electrolyser uses electrolysis to breakdown water into hydrogen and oxygen. The oxygen is dissipated into the atmosphere and the hydrogen is stored so it can be used for future generation. Due to the high cost of electrical production, only a small proportion of the current hydrogen production originates from electrolysis. Therefore, the most attractive option for future production is integrating electrolyser units with renewable resources such as wind or solar. In order to achieve this, an electrolyser must be capable of operating: with high efficiency; under good dynamic response; over a wide input range; under frequently changing conditions [2].

Recently a number of advancements have been made including higher efficiencies of 85%, wider input power capabilities, and more variable inputs. A new proton exchange membrane (PEM) has been developed instead of the preceding alkaline membranes. This can operate with more impure hydrogen, faster dynamic response, lower maintenance, and increased suitability for pressurization [2]. However, a PEM unit has lower efficiency (40–60%) so some development is still required. Electrolysers are modular devices so the capacity of a device is proportional to the number of cells that make up a stack. The largest commercial systems available can produce 485 Nm^3/h, corresponding to an input power of 2.5 MW. The lifetime of an electrolyser is proving difficult to predict due to its limited experience. However, research has indicated that the electrolyser unit will have the shortest lifespan within HESS. Some have predicted a lifespan in the region of 5–10 years but this is only an estimate [2].

4.9.1.1 Cost of hydrogen production

The estimated costs to produce power using an electrolyser are extremely varied. Predictions are as low as €300/kW [25] up to €1100/kW [2]. *ITM Power* in the UK claim to have produced an electrolyser that can operate with renewable sources, at a cost of $164/kW, and are currently planning to begin mass production in 2008 [26]. Maintenance costs are expected to be 3% of the capital cost [2].

4.9.1.2 Future of hydrogen production

Immediate developments are investigating the possibility of producing an electrolyser that can pressurise the hydrogen during electrolysis, as compressing the hydrogen after production is expensive and unreliable. Like all areas of HESS, the electrolyser needs a lot more development as well as technical maturity.

4.9.2 Hydrogen storage

A number of different options are currently available to store hydrogen:

1. *Compression*: The hydrogen can be compressed into containers or underground reservoirs. The cost of storing hydrogen in pressure vessels is $11/kWh to $15/kWh [2]. However, for underground reservoirs it is only $2/kWh [27]. This is a relatively simple technology, but the energy density and efficiency (65–70%) are low. Also, problems have occurred with the mechanical compression. However, this is at present the most common form of hydrogen storage for the transport industry, with the hydrogen compressed to approximately 700 bar (the higher the storage pressure, the higher the energy density, see Fig. 16). Although the energy required for the compression is a major drawback.
2. *Liquefied hydrogen*: The hydrogen can be liquefied by pressurising and cooling. Although the energy density is improved, it is still four times less than conventional petrol. Also, keeping the hydrogen liquefied is very energy intensive, as it must be kept below 20.27 K [28].
3. *Metal hydrides*: Certain materials such as nanostructured carbons and clathrate hydrate absorb molecular hydrogen. By absorbing the hydrogen in these materials, it can be easily transported and stored. Once required, the hydrogen is removed from the parent material. The energy density is similar to that obtained for liquefied hydrogen [28]. The extra material required to store the hydrogen is a major problem with this technique as it creates extra costs and mass. This is still a relatively new technology, so with extra development it could be a viable option; especially if the mass of material is reduced. Carbon-based absorption can achieve higher energy densities, but it has higher costs and even less demonstrations [2]. Both metal hydride or carbon-based absorption use thermal energy. This thermal heat could come from the waste heat of other processes with HESS, such as the electrolyser or fuel cell (FC), to improve overall efficiency.

Each storage technique is in the early stages of development and hence there is no optimum method at present with research being carried out in each area.

4.9.3 Hydrogen usage

There are two superior ways of using hydrogen:

1. internal combustion engine (ICE)
2. fuel cell

It is expected that the ICE will act as a transition technology while FCs are improving, because the modifications required to convert an ICE to operate on hydrogen are not very significant. However, the FC, due to its virtually emission-free, efficient and reliable characteristics, is expected to be the generator of choice for future hydrogen powered energy applications.

4.9.4 Fuel cell

A FC converts stored chemical energy, in this case hydrogen, directly into electrical energy. A FC consists of two electrodes that are separated by an electrolyte (see Fig. 17).

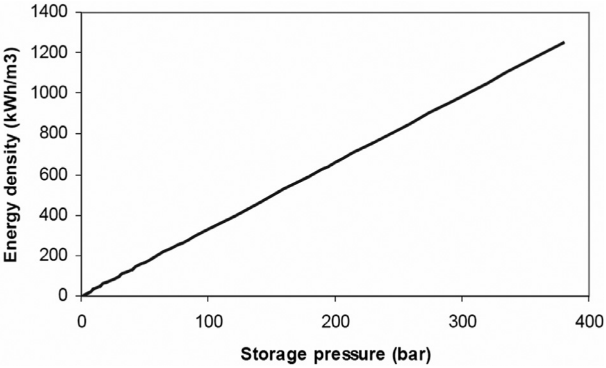


Figure 16: Energy density vs. pressure for hydrogen gas [2].

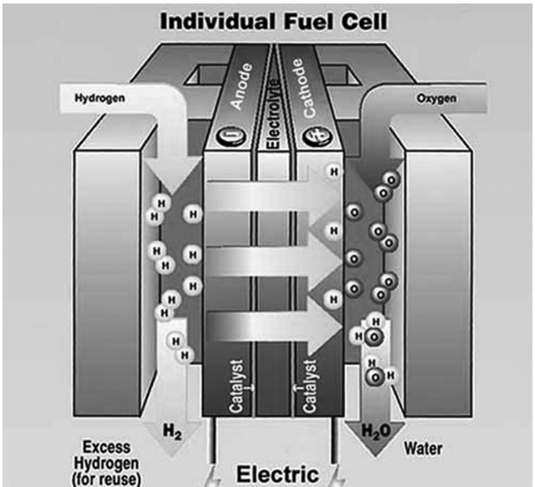


Figure 17: Fuel cell [29].

Hydrogen is passed over the anode (negative) and oxygen is passed over the cathode (positive), causing hydrogen ions and electrons to form at the anode. The electrons flow through an external circuit to produce electricity, whilst the hydrogen ions pass from the anode to the cathode. Here the hydrogen ions combine with oxygen to produce water. The energy produced by the various types of cells depends on the operation temperature, the type of FC, and the catalyst used (see Table 2). FCs do not produce any pollutants and have no moving parts. Therefore, theoretically it should be possible to obtain a reliability of 99.9999% in ideal conditions [30].

4.9.4.1 Cost of FC

All FCs cost between €500/kW and €8000/kW which is very high, but typical of an emerging technology [2]. These costs are expected to reduce as the technology ages and commercialization matures.

4.9.4.2 Future of FC

Immediate objectives for FCs include harnessing the waste heat more effectively to improve co-generation efficiency and also, combining FCs with electrolysers as a single unit. The advantage being lower capital costs although resulting in lower efficiency and increased corrosion [2]. FCs are a relatively new technology with high capital costs. However, with characteristics such as no moving parts, no emissions, lightweight, versatility and reliability, this is definitely a technology with a lot of future potential.

4.9.5 Disadvantages of HESS

The primary disadvantage with hydrogen is the huge losses due to the number of energy conversions required. Typically in a system that has high wind energy penetrations, by the time that hydrogen is actually being used for its final purpose it has gone through the following processes with corresponding efficiencies: (1) hydrogen is created by electrolysis – 85% efficient, (2) the hydrogen is stored – 65–70% efficient, (3) hydrogen is consumed in a FC car, power plant, or CHP unit – efficiency of 40–80%. This results in an overall efficiency ranging from 22 to 48%. In addition, this process assumes only one storage stage within the life of the hydrogen where as typically more than one storage stage would be necessary, i.e. stored when created, and stored at the location of use. Therefore, by implementing a "hydrogen economy", the efficiency of the system is very low that could result in very high energy costs and very poor utilization of limited resources such as wind or biomass. In summary, although the HESS offers huge flexibility, this flexibility is detrimental to the overall energy system efficiency.

4.9.6 Future of HESS

The use of hydrogen within the transport and electricity generation industries is expected to grow rapidly as electrolysis, storage techniques, and FCs become more commercially available. There are very ambitious hydrogen programs in the EU, USA and Japan, indicating increasing interest in hydrogen technology. Iceland is attempting to become the first 'hydrogen country' in the world by producing hydrogen from surplus renewable energy and converting its transport infrastructure from fossil fuels to hydrogen. In Norway, *Statkraft* plans to connect an electrolysis unit

Table 2: FC types [1].

Fuel cell	Electrolyte	Catalyst	Efficiency (%)	Operating temperature (°C)	Power output (kW)	Applications	Additional notes
Alkaline fuel cell (AFC)	Potassium hydroxide	Platinum	70	150–200	0.3–12	Widely used in the space industry (NASA)	Water produced by cell is drinkable. Can be easily poisoned by carbon dioxide (CO_2)
Polymer electrolyte membrane or proton exchange membrane (PEM)	Solid organic polymer	Platinum	45	80	50–250	Portable applications such as cars	Cell is sensitive to impurities so hydrogen used must be of good quality
Phosphoric acid fuel cell (PAFC)	Phosphoric acid	Platinum	40	150–200	200	Large stationary generation. Also co-generation (increases efficiency to 85%)	Can use impure hydrogen such as hydrogen from fossil fuels
Molten carbonate fuel cell (MCFC)	Potassium, sodium or lithium carbonate	Variety of non-precious metals	60	650	10–2000	Co-generation (increases efficiency to 85%)	High operating temperature and corrosive electrolyte result in short cell lifetime
Solid oxide fuel cells (SOFC)	Solid zirconium oxide	Variety of non-precious metals	60	1000	100	Utility applications. Prototype for co-generation exists (85% efficient)	High temperature causes slow start-up

to a large wind turbine and *Norsk Hydro* is continuing a project to provide Utsira Island with a wind hydrogen system. In Germany, *Siemens* and *P&T Technologies* are developing a wind hydrogen engine using an ICE. In the UK *Wind Hydrogen Limited* intend to develop large-scale wind hydrogen schemes. Finally, *HyGen* in California is developing a multi megawatt hydrogen generating and distributing network [2].

Car manufacturers are driving research in hydrogen for both the transport and infrastructure divisions. The automotive industry has engaged in setting up a strategy for the introduction of hydrogen to the transport sector with a number of single prototype projects advancing to fleet demonstrations [2]. Hydrogen is a serious contender for future energy storage due to its versatility. Once hydrogen can be produced effectively, it can be used for practically any application required. Consequently, producing hydrogen from renewable resources using electrolysis is currently the most desirable objective available. Primarily due to the versatility and potential of hydrogen to replace conventional fuel, "it is envisaged that the changeover to a hydrogen economy is less than 50 years from now" [2].

4.10 Thermal energy storage

Thermal energy storage (TES) involves storing energy in a thermal reservoir so that it can be recovered at a later time. A number of thermal applications are used instead of electricity to provide heating and cooling including aquifer thermal storage (ATS) and duct thermal storage (DTS). However, these are heat generation techniques rather than energy storage techniques and therefore will not be discussed in detail here. In terms of storing energy, there are two primary TES options. The first option is a technology which is used to supplement air conditioning in buildings and is displayed in Fig. 18. The second option is an energy storage system rather than a technology which will be discussed in more detail later.

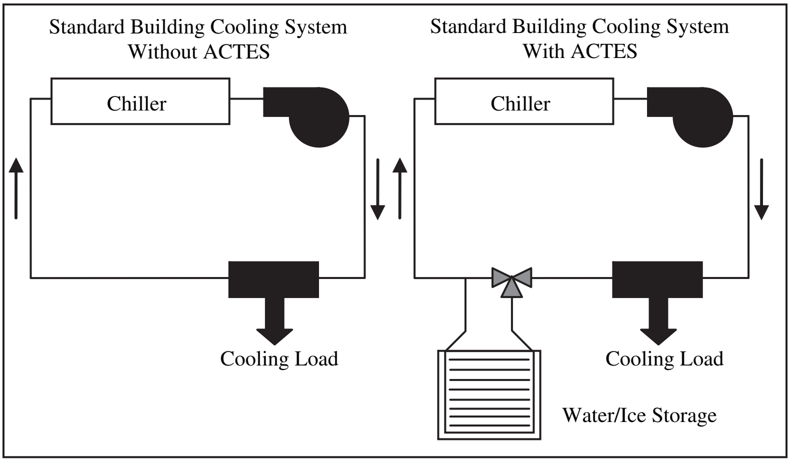


Figure 18: Air-conditioning thermal energy storage setup [3].

4.10.1 Air-conditioning thermal energy storage (ACTES)

The air-conditioning thermal energy storage (ACTES) units work with the air conditioning in buildings by using off-peak power to drive the chiller to create ice. During the day, this ice can be used to provide the cooling load for the air conditioner. This improves the overall efficiency of the cycle as chillers are much more efficient when operated at night time due to the lower external temperatures. Also, if ACTES units are used, the size of the chiller and ducts can be reduced. Chillers are designed to cope with the hottest part of the hottest day possible, all day. Therefore, they are nearly always operating below full capacity. If ACTES facilities are used, the chiller can be run at full capacity at night to make the ice and also at full capacity during the day; with the ice compensating for shortfalls in the chiller capacity. ACTES units lose approximately 1% of their energy during storage [3].

4.10.1.1 Cost of ACTES

If ACTES is installed in an existing building, it costs from $250 to $500 per peak kW shifted, and it has a payback period from 1 to 3 years. However, if installed during construction, the cost saved by using smaller ducts (20–40% smaller), chillers (40–60% smaller), fan motors, air handlers and water pumps will generally pay for the price of the ACTES unit. As well as this, the overall air conditioning cost is reduced by 20–60% [3].

4.10.1.2 Future of ACTES

Due to the number of successful installations that have already occurred, this technology is expected to grow significantly where air-conditioning is a necessity. It is however, dependent on the future market charges that apply, as this technology benefits significantly from cheaper off-peak power and demand charges. Finally, ACTES units will have to compete with other building upgrades such as lighting and windows, for funding in the overall energy saving strategies enforced [3].

4.10.2 Thermal energy storage system

The TESS can also be used very effectively to increase the flexibility within an energy system. As mentioned previously in this chapter, by integrating various sectors of an energy system, increased wind penetrations can be achieved due to the additional flexibility created. Unlike the HESS which enabled interactions between the electricity, heat and transport sectors, TES only combines the electricity and heat sectors with one another. By introducing district heating into an energy system, then electricity and heat can be provided from the same facility to the energy system using combined heat and power (CHP) plants. This brings additional flexibility to the system which enables larger penetrations of intermittent renewable energy sources. To illustrate the flexibility induced by TES on such a system, a snapshot of the power during different scenarios is presented below. The system in question contains a CHP plant, wind turbines, a thermal storage, a hot water demand, and an electrical demand as illustrated in Fig. 19.

During times of low wind power, a lot of electricity must be generated by the CHP plants to accommodate for the shortfall power production. As a result, a lot of hot water is also being produced from the CHP plant as seen in Fig. 19a. The high production of hot water means that production is now greater than demand, and consequently, hot water is sent to the thermal storage. Conversely, at times of high wind power, the CHP plants produce very little electricity and hot water. Therefore, there is now a shortage of hot water so the thermal storage is used to supply the shortfall, as seen in Fig. 19b.

4.10.2.1 Disadvantages of TESS

Similar to the HESS, the primary disadvantage with a TESS is the large investments required to build the initial infrastructure. However, the TESS has two primary advantages: (1) the energy system efficiency is improved with the implementation of a TESS. CHP production is approximately 85–90% efficient while conventional power plants are only 40% efficient, and (2) this technique has already been implemented in Denmark so it is a proven solution. On the negative side TES does not improve flexibility within the transport sector like the HESS, but this is inferior to the advantages it possesses. Therefore, in summary, the TESS does have disadvantages, but these are small in comparison to the advantages.

4.10.2.2 Future of TESS

Due to the efficiency improvements and maturity of this system, it is very likely that it will become more prominent throughout the world. Not only does it enable the utilization of more intermittent renewable energy (such as wind), but it also optimises the use of fuel within power plants, something that will become critical as biomass becomes more prominent. This system has been put into practice in Denmark which has the highest wind penetration in the world. In addition, Lund has

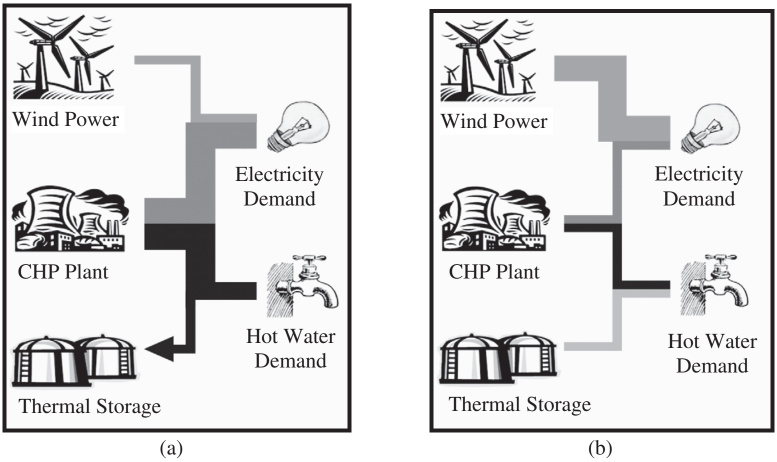


Figure 19: Energy system with district heating and thermal energy storage during: (a) a low wind scenario and (b) a high wind scenario.

outlined a roadmap for Denmark to use this setup in achieving a 100% renewable energy system at a lower cost than a conventional energy system [31]. Therefore, it is evident this technology can play a crucial role in future energy systems.

4.11 Electric vehicles

The final energy storage system that will be discussed in this chapter is the deployment of EVs. Once again, system flexibility and hence feasible wind penetrations are increased with the introduction of EVs into the transport sector. As illustrated in Fig. 20, EVs can feed directly from the power grid while stationary, at individual homes or at common recharging points, such as car parks or recharging stations. By implementing EVs, it is possible to make large-scale BES economical, combat the huge oil dependence within the transport sector and drastically increase system flexibility (by introducing the large-scale energy storage) [32]. Consequently, similar to the HESS and the TESS, EVs also provide a method of integrating existing energy systems more effectively.

4.11.1 Implementation of EV technology

EVs can be classified under three primary categories: (1) battery electric vehicles (BEV), (2) smart electric vehicles (SEVs) and (3) vehicle to grid (V2G).

4.11.2 Applications of EV technology

BEVs are plugged into the electric grid and act as additional load. In contrast, SEVs have the potential to communicate with the grid. For example, at times of high wind production, it is ideal to begin charging EVs to avoid ramping centralised production. In addition, at times of low wind production, charging vehicles should be avoided if possible until a later stage. V2G EVs operate in the same way

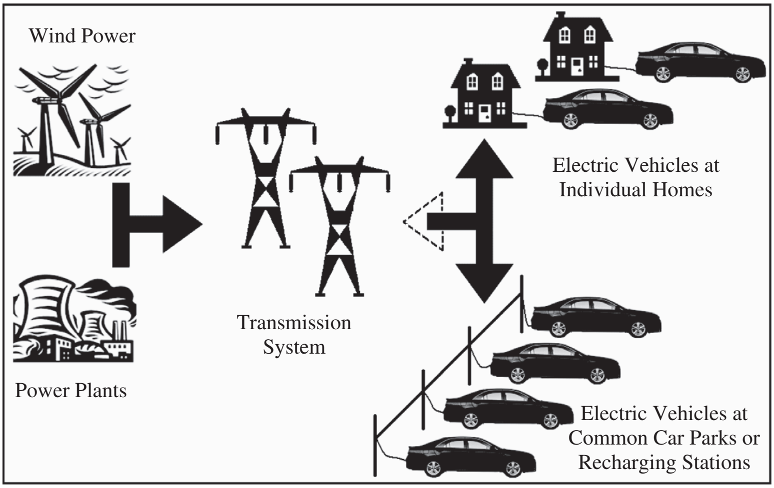


Figure 20: Schematic of electric vehicles and electric power grid.

as SEV, however, they have the added feature of being able to supply power back to the grid. This increases the level of flexibility within the system once again. All three types of EVs could be used to improve wind penetrations feasible on a conventional grid, with each advancement in technology increasing the wind penetrations feasible from approximately 30–65% [32] (from BEV to V2G).

4.11.3 Cost of EV technology

The costs associated with EVs are different to the costs quoted for other storage technologies. Consumers are not buying EVs to provide energy storage capacity for the grid, instead they are buying EVs as a mode of transport. Therefore, it is difficult to compare the costs of EVs under the conventional $/kW and $/kWh that other storage systems are compared with. As a result, below is a comparison between the price of EVs and conventional vehicles, as this comparison is more relevant when considering the uptake of EVs. Figure 21 illustrates the cost of owning a BEV and a conventional EV over a 105,000 km lifetime, with 25% of its life in urban areas. It is evident from Fig. 21 that BEVs are approximately 20% more expensive than conventional vehicles: while SEVs and V2G would be even more expensive, but these are still at the development stage. As SEVs and V2G EVs will enable significantly larger wind penetrations on the power grid than BEVs [32],

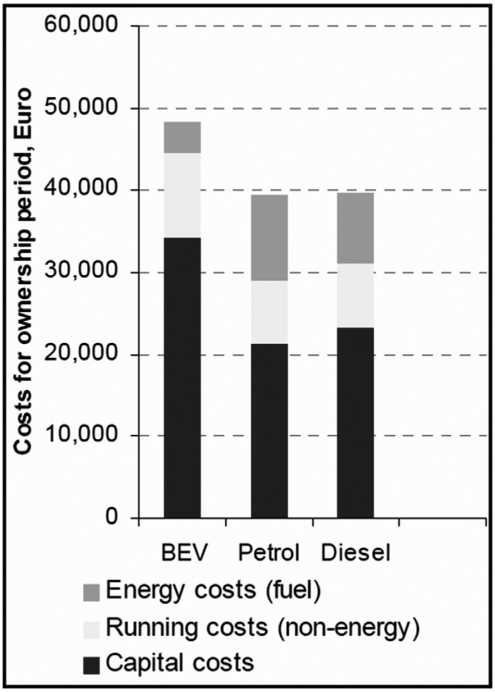


Figure 21: Cost of battery electric vehicles and conventional vehicles for a lifetime of 105,000 km (25% of which is urban driving) [33].

it is likely that economic incentives will be necessary to attract consumers to purchase SEV and V2G vehicles.

4.11.4 Disadvantages of EV technology

The primary disadvantage with EVs is the initial investment to establish the required infrastructure. Transmission lines will need to be upgraded to allow for high power capacities to and (in the case of V2G) from the electric cars, battery banks or charging stations will be required to replace conventional refuelling stations, and maintenance services will need to be established as we transfer from conventional ICEs to electric motors. In addition, travelling habits may need to be altered due to the alternative limitations associated with EVs instead of conventional vehicles, such as driving styles and time required for refuelling. Finally, the remaining issue with EVs is the driving range that can be obtained. Currently, hydrogen vehicles have a much larger range than EVs, although hydrogen vehicles are much less efficient. Therefore, depending on which of these factors is more important for different energy systems will most likely decide which of these technologies is preferred.

4.11.5 Future of EV technology

Electric vehicles are most likely going to be a key component in a number of future energy systems with large penetrations of intermittent renewable energy. This is primarily due to the two advantages mentioned in the introduction to this section: they reduce oil dependence and provide affordable large-scale energy storage. However, as mentioned already, alternative options such as hydrogen vehicles may reduce the attraction to EVs within energy systems which prioritise range over energy efficiency. However, steps are being taken in Europe, Japan and elsewhere to improve battery technology to the point where a 500 km range is standard. Key developments, e.g. in nanostructured lithium batteries may triple the energy density which can be achieved if this technology can be proven and manufactured cost effectively.

5 Energy storage applications

Energy storage devices can accommodate a number of network requirements. These include as follows [2].

5.1 Load management

There are two different aspects to load management:

1. *Load levelling*: Using off-peak power to charge the energy storage device and subsequently allowing it to discharge during peak demand. As a result, the overall power production requirements becomes flatter and thus cheaper base-load power production can be increased.
2. *Load following*: Energy storage device acts as a sink when power required falls below production levels and acts as a source when power required is above production levels.

Energy devices required for load management must be in the 1–100+ MW range as well as possessing fast response characteristics.

5.2 Spinning reserve

Spinning reserve is classified under two categories:

1. *Extremely fast response spinning reserve*: power capacity that is kept in the state of 'hot-stand-by'. As a result it is capable of responding to network abnormalities quickly.
2. *Conventional spinning reserve*: power capacity that requires a slower response.

Energy storage devices used for spinning reserve usually require power ratings of 10–400 MW and are required between 20 and 50 times per year.

5.3 Transmission and distribution stabilization

Energy storage devices are required to stabilise the system after a fault occurs on the network by absorbing or delivering power to generators when needed to keep them turning at the same speed. These faults induce phase angle, voltage and frequency irregularities that are corrected by the storage device. Consequently, fast response and very high power ratings (1–10 MW) are essential.

5.4 Transmission upgrade deferral

Transmission line upgrades are usually separated by decades and must be built to accommodate likely load and generating expansions. Consequently, energy storage devices are used instead of upgrading the transmission line until such time that it becomes economical to do so. Typically, transmission lines must be built to handle the maximum load required and hence it is only partially loaded for the majority of each day. Therefore, by installing a storage device, the power across the transmission line can be maintained constant even during periods of variable supply and demand. Then when demand increases, the storage device is discharged preventing the need for extra capacity on the transmission line to supply the required power. Therefore, upgrades in transmission line capacities can be postponed. Storage devices for this application must have a power capacity of kW to several hundreds of megawatts and a storage capacity of 1–3 h. Currently the most common alternative is portable generators; with diesel and fossil fuel power generators as long-term solutions and biodiesel generators as a short-term solution.

5.5 Peak generation

Energy storage devices can be charged during off-peak hours and then used to provide electricity when it is the most expensive, during short peak production periods.

5.6 Renewable energy integration

In order to aid the integration of renewable resources, energy storage can be used to:

1. Store renewable energy during off-peak time periods for use during peak hours (diurnal time-scale)
2. Match the output from renewable resources to the load required in the electricity market time-scale (quarter hour)
3. Smooth output fluctuations from a renewable resource in the millisecond to second time-scale
4. Significantly enhance the capacity factor (output which can be considered reliable) and associated payments attributable to wind
5. Facilitate the maximum inclusion of renewable electricity, by storing electricity from conventional generation for periods when total generating capacity cannot supply demand

A storage system used with renewable technology must have a power capacity of 10 kW to 100 MW, have fast response times (in some cases less than a second), excellent cycling characteristics (100–1000 cycles per year) and a good lifespan.

5.7 End-use applications

A survey in the US estimated that losses due to end-use and UPS applications were between $119 billion and $189 billion [2]. The most common end-use application is power quality which primarily consists of voltage and frequency control. Transit and end-use ride-through are applications requiring short power durations and fast response times, in order to level fluctuations, prevent voltage irregularities and provide frequency regulation. This is primarily used on sensitive processing equipment.

5.8 Emergency backup

This is a type of UPS except the units must have longer energy storage capacities. The energy storage device must be able to provide power while generation is cut altogether. Power ratings of 1 MW for durations up to 1 day are most common. For outages of several hours, days or weeks, diesel generators are more cost effective.

5.9 Demand side management

Demand side management (DSM) involves actions that encourage end-users to modify their level and pattern of energy usage. Energy storage can be used to provide a suitable sink or source in order to facilitate the integration of DSM. Conversely, DSM can be used to reduce the amount of energy storage capacity required in order to improve the network. Ultimately, the goal is to match consumption with generation by attributing some intelligence and control ability to the consumer, first at the industrial-scale and then domestic with tariff and other incentives for peak avoidance.

6 Comparison of energy storage technologies

To begin a brief comparison of the storage technologies within each category is discussed. These include: large power and storage capacities (PHES, UPHES, CAES); medium power and storage capacities (BES, FBES); large power or storage capacities (SCES, FES, SMES) energy storage systems (HESS, TESS, EVs). This is followed by an overall comparison of all the storage technologies.

6.1 Large power and energy capacities

The only devices capable of large power (>50 MW) and energy capacities (>100 MWh) are PHES, UPHES and CAES.

New PHES facilities are unlikely to be built as upgrades continue to prove successful. Once upgrades have been completed on existing PHES facilities, like all large-scale energy storage technologies the potential for PHES will depend heavily on the availability of suitable sites. It is widely believed that there are a limited number of suitable sites available for PHES. However, recent studies completed have illustrated the potential for seawater PHES [6, 34] as well as the potential for many more freshwater PHES sites than originally anticipated [35]. Therefore, if results continue in this fashion, PHES may only be constrained by economics and not technical feasibility, indicating that it could become a very important technology as fuel prices continue to rise in the future.

In theory UPHES could be a major contender for the future as it operates under the same operating principals as PHES: therefore, almost all of the technology required to construct such a facility is already available and mature. In addition, sites for UPHES will not be located in mountainous, isolated regions where construction is difficult and expensive. However, UPHES will still have unique site constraints of its own as it will require a suitable underground reservoir. Until such time that an extensive investigation is completed analysing the availability of such reservoirs, the future of UPHES will be uncertain.

Finally, the attractiveness of CAES depends on your opinion regarding the availability of gas and once again, the potential for suitable locations. It is a flexible, reliable, and efficient technology but it still needs gas to operate and an underground storage reservoir for the compressed air. Consequently, like PHES and UPHES, the potential for CAES will depend heavily on the availability of suitable locations. However, in addition the future of CAES may be decided based on the future availability of gas within an energy system. CAES by its nature is capital intensive and hence a long-term commitment. Therefore, if the energy system considering CAES has long-term ambitions to eliminate a dependence on gas, then this should be accounted for when analysing the feasibility of CAES.

In conclusion, it is evident that large-scale energy storage facilities all share one key issue: the availability of suitable locations. However, based on recent studies, suitable sites for PHES may be more prominent than originally anticipated. Therefore, until such time that the other large-scale storage technologies can display a similar potential for new facilities, it is likely that PHES will continue to lead the way in this category.

6.2 Medium power and energy capacities

This section includes BES and FBES. The only major contender from the BES storage technologies for future large-scale projects is the NaS battery. LA and NiCd will always be used for their existing applications but further breakthroughs are unlikely. FBES technologies (including VR, PSB and ZnBr) are all currently competing for the renewable energy market. Demonstration results for these batteries will be decisive for their future. It is worth noting that flow batteries are much more complex than conventional batteries. This is the reason conventional batteries will always be required. Conventional batteries are simple but constrained (power and storage capacities are coupled) while flow batteries are flexible but complex (power and storage capacities are independent but a number of extra parts required). The other key issue for this category will be the development of EVs. If technological advancements continue within EVs, then large-scale BES will most probably play an important role in future energy systems but not as stand-alone systems. Therefore, the future of this sector is very uncertain as various technologies continue to develop.

6.3 Large power or storage capacities

FES must be optimised to solve storage capacity issues (high speed flywheels, max 750 kW for 1 h) or power capacity issues (low speed flywheels, max 1650 kW for 120 s). SCES and SMES are only useful for power capacity issues. Therefore, FES, SCES and SMES are all used for power issues where a lot of power is required very fast. These technologies only differ in power capacity. FES is ideal for small power (up to 750 kW), SCES for medium power (up to 1 MW) and SMES for large power issues (up to 10 MW). The optimum technology depends on the power required for each specific application. Due to this very specific characteristic, these technologies are likely to be used for their specific purposes well into the future such as uninterruptable power supply.

6.4 Overall comparison of energy storage technologies

It is very difficult to compare the various types of energy storage techniques to one another as they are individually ideal for certain applications but no technology is perfect for everything. Consequently, for the purposes of this chapter, a number of illustrations are provided indicating the capabilities of each energy storage technology in relation to one another (see Figs. 22–26). This is followed by a table outlining the detailed characteristics of each storage technology (see Table 3) and a table indicating the cost of each technology (see Table 4). Finally, there is a table specifying the applications that each storage technology is suitable for (see Table 5).

6.5 Energy storage systems

The three energy storage systems that have been discussed above are HESS, TESS and EVs. The HESS provides an excellent level of flexibility within an energy system, by enabling the electricity, heat and transport sectors to interact

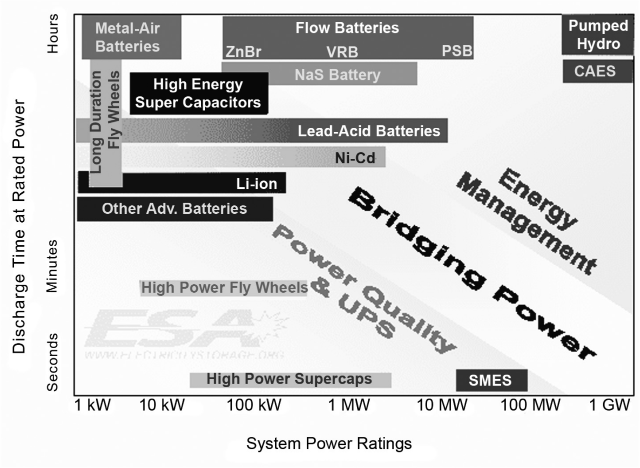


Figure 22: Discharge time vs. power ratings for each storage technology [37].

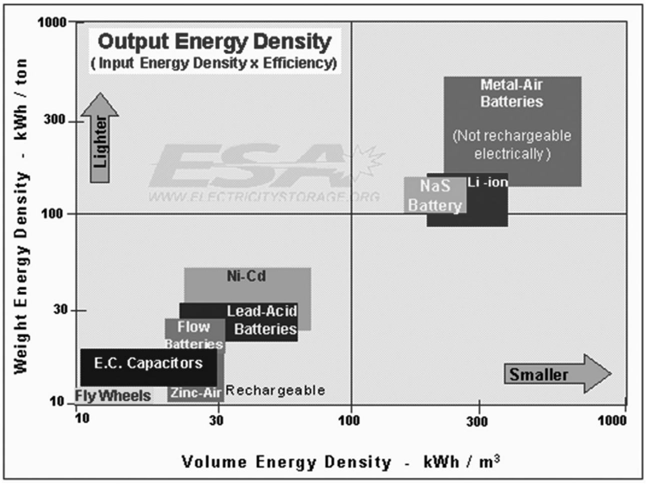


Figure 23: Weight energy density vs. volume energy density for each technology [37].

with one another. However, the primary disadvantage is the poor efficiencies due to the number of conversion required between creating hydrogen and using hydrogen. In contrast, the TESS increases the efficiency of the overall energy system. However a thermal energy system does not incorporate the transport sector. As a result, EVs (the third energy system discussed) are often combined with the TESS. Connolly *et al.* compared such a system with a hydrogen system and found that the TESS/EV energy system only needs 85% of the fuel that a HESS requires [37]. In addition, the TESS has already been implemented in Denmark and thus is a much more mature solution that a hydrogen economy.

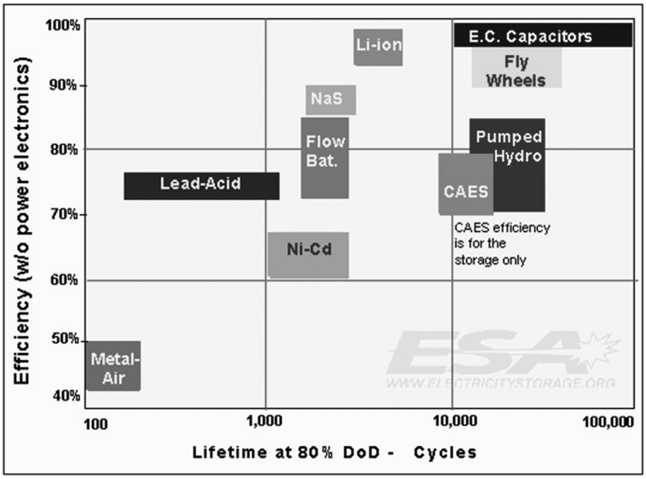


Figure 24: Efficiency and lifetime at 80% depth of discharge for each technology [37].

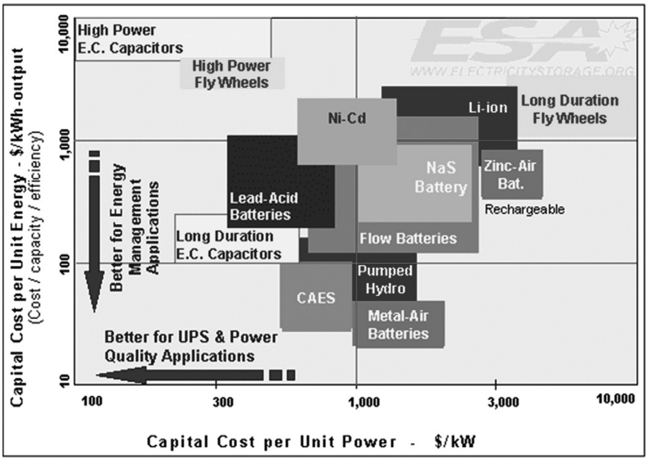


Figure 25: Capital cost for each technology [37].

However, if energy production is cheap or baseload renewable energy (i.e. biomass) is limited, the inefficiencies of the hydrogen energy system may be attractive. Therefore, a lot of potential exists but more research is required to truly quantify the benefits and drawbacks of each system.

Finally, it is evident from this chapter, that energy storage systems provide a much more promising solution to the integration of intermittent renewable energy than individual technologies. Energy storage technologies will most likely improve the penetrations of renewable energy on the electricity network but disregard the heat and transport sectors. Consequently, energy storage systems could be the key to finally replacing the need for fossil fuel with renewable energy.

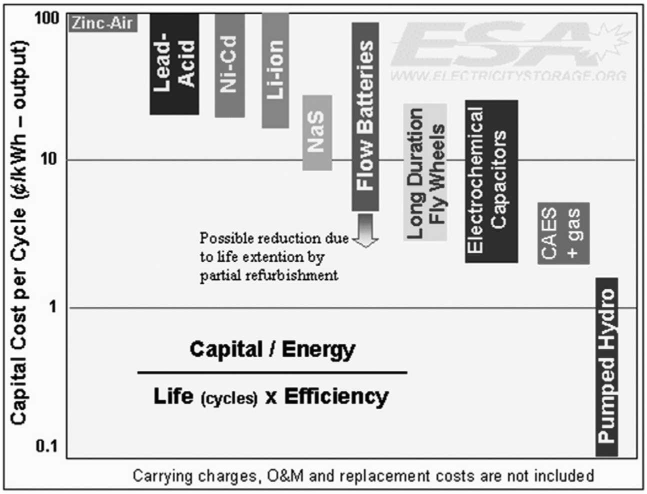


Figure 26: Cost per cycle for each technology [37].

7 Energy storage in Ireland and Denmark

Ireland and Denmark are very interesting countries as case studies for the deployment of energy storage systems. They have relatively small national electricity networks and large wind resources. They differ in that while Denmark is deeply interconnected to the electricity grids of continental Europe, Ireland as an island nation is not. Neither have substantial fossil fuel resources, but Ireland in particular is among the most dependent (92.6% in 2008) countries worldwide on imported fossil fuels for its electricity generation. In order to reduce greenhouse gases, Ireland's primary objective is to produce at least 40% of its electricity from renewable resources by 2020. Currently, Ireland's wind generating capacity has just surpassed 1000 MW, approximately 13% of the total Irish network capacity (see Table 6). However, previous reports had indicated that grid stability can be affected once wind capacity passed 800 MW [3]. As a result, Ireland will need to address the effects of grid intermittency in the immediate future.

Energy storage for an electric grid provides all the benefits of conventional generation such as, enhanced grid stability, optimised transmission infrastructure, high power quality, excellent renewable energy penetration and increased wind farm capacity. The main downsides of energy storage are the additional cost and the round-trip efficiency loss which may be as much as 30%. However, the operation of energy storage systems to store renewable generated electricity produces no carbon emissions and they do not rely on imported fossil fuels. As a result, energy storage is a very attractive option for increasing wind penetration onto the electric grid when it is needed.

However, currently Ireland's solution to the grid problems associated with the intermittency of wind generation is grid interconnection. EirGrid is in the process

Table 3: Characteristics of storage technologies [4].

	Power rating	Discharge duration	Response time	Efficiency	Parasitic losses	Lifetime	Maturity
Pumped hydro	100 – 4000 MW	4 – 12 h	sec – min	0.7 – 0.85	evaporation	30 y	commercial
CAES (in reservoirs)	100 – 300 MW	6 – 20 h	sec – min	0.64	-	30 y	commercial
CAES (in vessels)	50 – 100 MW	1 – 4 h	sec – min	0.57	-	30 y	concept
Flywheels (low speed)	<1650 kW	3 – 120 s	<1 cycle	0.9	~1%	20 y	commercial products
Flywheels (high speed)	<750 kW	<1 h	<1 cycle	0.93	~3%	20 y	prototypes in testing
Super-capacitors	<100 kW	<1 m	<1/4 cycle	0.95	-	10,000 cycles	some commercial products
SMES (Micro)	10 kW – 10 MW	1 s – 1 m	<1/4 cycle	0.95	~4%	30 y	commercial
SMES	10 – 10 MW	1 – 30 m	<1/4 cycle	0.95	~1%	30 y	design concept
Lead-acid battery	<50 MW	1 m – 8 h	<1/4 cycle	0.85	small	5 – 10 y	commercial
NaS battery	<10 MW	<8 h	n/a	0.75 – 0.86	5kW/kWh	5 y	in development
ZnBr flow battery	<1 MW	<4 h	<1/4 cycle	0.75*	small	2,000 cycles	in test/commercial units
V redox flow battery	<3 MW	<10 h	n/a	70 – 85*	n/a	10 y	in test
Polysulphide Br flow battery	<15 MW	<20 h	n/a	60 – 75*	n/a	2,000 cycles	in test
Hydrogen (Fuel Cell)	<250 kW	as needed	<1/4 cycle	0.34 – 0.40*	n/a	10 – 20 y	in test
Hydrogen (Engine)	<2 MW	as needed	seconds	0.29 – 0.33*	n/a	10 – 20 y	available for demonstration

*AC-AC efficiency.

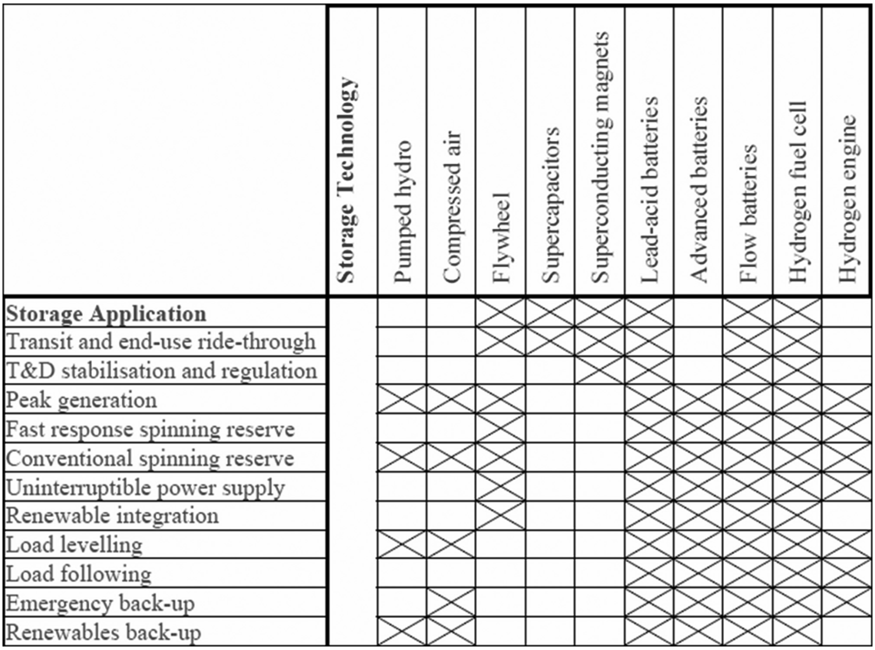
**Discharge device. An independent charging device (electrolyser) is required.

Table 4: Cost characteristics of storage technologies [2].

	Capital cost			O&M cost				
	Power-related cost ($/kW)	Energy-related cost ($/kWh)	BOP ($/kWh)	Fixed ($/kW-y)	Variable (c$/kWh)	Cost certainty	Environmental issues	Safety issues
Pumped hydro	600	0 – 20	included	3.8	0.38	■	reservoir	exclusion area
CAES (in reservoirs)	425 – 480	3 – 10	50	1.42	0.01	▦	gas emissions	none
CAES (in vessels)	517	50	40	3.77	0.27	□	gas emissions	pressure vessels
Flywheels (low speed)	300	200 – 300	~80			■	-	containment
Flywheels (high speed)	350	500 – 25,000	~1000	7.5	0.4	▨	-	containment
Super-capacitors	300	82,000	10,000	5.55	0.5	▨	-	-
SMES (Micro)	300	72,000	~ 10,000	26	2	▦	-	magnetic field
SMES	300	2,000	~ 1,500	8	0.5	□	-	magnetic field
Lead-acid battery	200 – 300	175 – 250	~ 50	1.55	1.0	■	lead disposal	lead disposal, H2
NaS battery	259	245	~ 40	n/a	n/a	▨	chemical handling	thermal reaction
ZnBr flow battery	1,500	200	included	n/a	n/a	▨	chemical handling	chemical handling
V redox flow battery	n/a	175 –190	n/a	n/a	n/a	▨	chemical handling	chemical handling
Polysulphide Br flow battery	1,200	175 –190	n/a	n/a	n/a	▨	chemical handling	chemical handling
Hydrogen (Fuel Cell)	1100 – 2600	2 – 15	n/a	10.0	1.0	▦	-	-
Hydrogen (Engine)	950 – 1850	2 – 15	n/a	0.7	0.77	■	emissions	-

■ Price list available ▦ Price quotes available ▨ Cost determined each project □ Costs estimated

Table 5: Technical suitability of storage technologies to different applications [2].



	Storage Technology	Pumped hydro	Compressed air	Flywheel	Supercapacitors	Superconducting magnets	Lead-acid batteries	Advanced batteries	Flow batteries	Hydrogen fuel cell	Hydrogen engine
Storage Application				X	X	X	X		X	X	
Transit and end-use ride-through				X	X	X	X		X	X	
T&D stabilisation and regulation						X	X		X	X	
Peak generation		X	X	X			X	X	X	X	X
Fast response spinning reserve				X			X	X	X	X	X
Conventional spinning reserve		X	X	X			X	X	X	X	X
Uninterruptible power supply				X			X	X	X	X	X
Renewable integration				X			X	X	X	X	
Load levelling		X	X				X	X	X	X	X
Load following							X	X	X	X	X
Emergency back-up			X				X	X	X	X	X
Renewables back-up		X	X				X	X	X	X	

Table 6: Network capacity for Ireland and Northern Ireland (correct as of May 2009).

Item	Republic of Ireland (MW)	Northern Ireland (MW)	All-Island (MW)
Total conventional capacity (MW)	6336.3	1968*	8902.3♦
Total wind capacity (MW)	1077	182**	1421.5♦
Total	7413.3	2150	10,323.8♦

Will increase to *2566 MW and **408 MW by August 2009.
♦Predicted values for August 2009.

of constructing a 500 MW interconnector to Wales that will allow for importing and exporting of electricity to and from Great Britain. Effectively, Great Britain will be Ireland's 'storage' device: excess electricity can be sold when the wind is blowing and electricity can be imported when it is not. A similar approach to improve grid stability was carried out in Denmark who installed large interconnectors to neighbouring Germany, Norway and Sweden (see Table 7).

However, Denmark discovered that they were only using approximately 500 MW of their wind generation at any time (see Fig. 27). The rest was being exported to Germany, Norway and Sweden.

Although this makes it possible for Denmark to implement a large amount of wind generation, Denmark is not only exporting wind power, but also its benefits. Firstly, Denmark exports its wind power cheaper than it buys power back. When excess wind power is available, Denmark needs to get rid of it, so Norway and Sweden pause their hydrogenerating facilities and buy cheaper wind power from Denmark. When wind production is low, Norway and Sweden turn back on their hydrogenerators, which have now stored large amounts of water, and sell power back to Denmark at a higher tariff. By using Great Britain as a power sink/source to accommodate wind power, Ireland too could face similar financial losses whilst exporting wind power.

Also, Germany uses the wind power generated in Denmark to reduce its own CO_2 emissions. Although Denmark is generating green power it is not profiting in terms of CO_2 reductions (green value). Consequently, if interconnection is continued to be used in Ireland to integrate wind power onto the grid, Ireland's green power could be used to reduce the CO_2 emissions of Great Britain rather than Ireland. By using energy storage technologies instead of interconnection, Ireland

Table 7: Grid interconnection in and out of Denmark.

Country	Interconnection from Denmark (MW)	Interconnection to Denmark (MW)
Germany	1200	800
Norway	950	1000
Sweden	610	580
Total	2760	2380

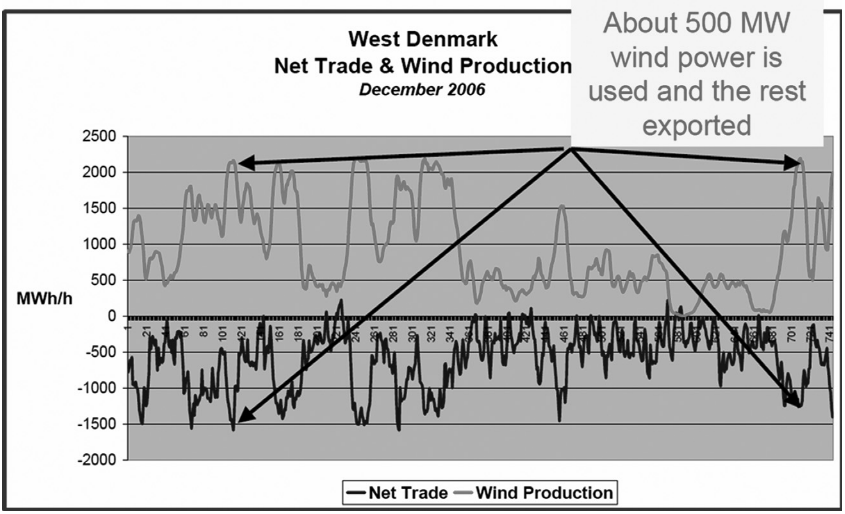


Figure 27: Wind production and interconnection trading for Denmark in December 2006 [4].

can develop an independent, stable and green electric grid. As renewable electricity deployment continues to expand worldwide at a rate of 30% p.a. for both wind and solar, these same issues will arise in larger countries. When the proportion of renewables on any country's electricity is large enough to require significant export and import activity, issues of interconnection, storage and green value will need to be addressed.

8 Conclusions

No one technology has all the ideal characteristics required for optimal grid integration of renewables. It is most likely that PHES (depending on topography, geology and feasibility), and FBES, will be the most attractive options for integrating renewable energy in the future because:

- PHES is a mature, proven, large-scale storage system that can act as an energy reservoir during times of excess electricity-production or as a producer during shortages in energy supply. In addition, recent studies have indicated that the lack of suitable sites may not be as severe as originally anticipated. Therefore, it is anticipated that PHES still has a role to play when integrating amounts of renewable energy.
- FBES facilities can act as the 'middle-man' between the grid and large-scale PHES facilities. As FBES are site-specific they can built where PHES is not an option and flexibility can compensate for the disadvantages of PHES.

In addition to the technologies identified above, all three energy storage systems discussed in this chapter have a huge potential in improve renewable energy penetrations in the future.

- The HESS is establishing itself as a serious contender for future power production more and more especially in the transport sector. Therefore, even if the HESS is not utilised for converting the hydrogen back to electricity, it is evident that hydrogen will probably be required for other applications such as heating or transport in the future. Therefore, it is an area that has a lot of future potential even though it can be an inefficient process.
- The TESS is not only capable of increasing the wind penetrations feasible within an energy system, but it also increases the overall efficiency of the energy system. Even more importantly, this technology has already been proven within the Danish energy system and hence does not carry the same risks as other options. However, the primary drawback of the TESS in comparison to the HESS is the transport sector: TESS does not account for the transport sector. However, this can be counteracted by combining the TESS with EVs.
- EVs are more efficient than both hydrogen and conventional vehicles. They also have the potential to make large-scale BES economical and hence vastly improve the flexibility within energy system. By combining EVs with the TESS huge reductions in fuel demands can be achieved as well as drastic increases in the potential to integrate renewable energy. Also, Lund has shown that this

technique can be extended further to a 100% renewable energy system [31]. As a result, this combination is one of the most promising solutions in the transition from a fossil fuel to a renewable energy system.

- All three energy storage systems can drastically improve the integration of wind energy. However, due to the very large initial investment required to implement any of these energy systems, it is very likely that either the HESS or the TESS/EVs combination scenario will begin to compete with one another as the primary solution to integrating renewable energy. To decide which of these is the most beneficial will depend on whole range of issues including: (1) wind, wave, solar and tidal resource available; (2) biomass potential; (3) electricity, heating and transport demands; (4) energy system infrastructure already in place and so on.

In relation to the other technologies discussed in this chapter BES, FES, SMES, SCES and ACTES are always going to be used within the power sector but future operational breakthroughs are unlikely. Finally, although CAES reduces the amount of gas required it still uses gas for electricity production and therefore is likely to be a transition technology rather than a long-term solution depending on future availability of gas within the energy system.

After considering all the technologies, it is clear that integrating the electricity, heat and transport sectors of an energy system is probably the most effective method of increasing renewable energy usage. The additional flexibility that occurs by integrating these systems enables the grid operator to utilise the intermittent renewable resources more effectively. It is only then, after all these systems have been joined together, that individual energy storage technologies should be added as additional flexibility, especially if under current economic constraints.

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