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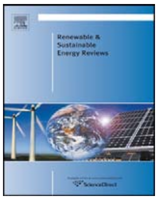

Overview of current and future energy storage technologies for electric power applications

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ABSTRACT

In today's world, there is a continuous global need for more energy which, at the same time, has to be cleaner than the energy produced from the traditional generation technologies. This need has facilitated the increasing penetration of distributed generation (DG) technologies and primarily of renewable energy sources (RES). The extensive use of such energy sources in today's electricity networks can indisputably minimize the threat of global warming and climate change. However, the power output of these energy sources is not as reliable and as easy to adjust to changing demand cycles as the output from the traditional power sources. This disadvantage can only be effectively overcome by the storing of the excess power produced by DG-RES. Therefore, in order for these new sources to become completely reliable as primary sources of energy, energy storage is a crucial factor. In this work, an overview of the current and future energy storage technologies used for electric power applications is carried out. Most of the technologies are in use today while others are still under intensive research and development. A comparison between the various technologies is presented in terms of the most important technological characteristics of each technology. The comparison shows that each storage technology is different in terms of its ideal network application environment and energy storage scale. This means that in order to achieve optimum results, the unique network environment and the specifications of the storage device have to be studied thoroughly, before a decision for the ideal storage technology to be selected is taken.

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1. Introduction

In today's world, the need for more energy seems to be ever-increasing. Both households and industries require large amounts of power. At the same time the existing means of energy production face new problems. International treaties aim to limit the

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levels of pollution, global warming prompts action to reduce the output of carbon dioxide and several countries have decided to decommission old nuclear power plants and not build new ones. In addition, the unprecedented global increase in energy demand has meant that the price of conventional energy sources has risen dramatically and that the dependence of national economies on a continuous and undistorted supply of such sources has become critical.

Such development brings about the need to replace old energy production methods with new ones. While several are in development, including the promising nuclear fission power, other production methods are already in commercial use. The penetration of renewable energy sources and of other forms of potential distributed generation sources is increasing worldwide. These types of energy sources often rely on the weather or climate to work effectively, and include such methods as wind power, solar power and hydroelectricity in its many forms.

These new sources of energy have some indisputable advantages over the older methods. At the same time, they present new challenges. The output of the traditional methods is easy to adjust according to the power requirements. The new energy sources are based more directly on harnessing the power of the nature and as such their peak power outputs may not match the power requirements. They may exhibit large fluctuations in power output in monthly or even annual cycles. Similarly, the demand can vary monthly or annually. Therefore, in order for these new sources to become completely reliable as primary sources of energy, energy storage is a crucial factor. Essentially, energy from these sources must be stored when excess is produced and then released, when production levels are less than the required demand. Energy storage technologies form therefore an integral and indispensable part of a reliable and effective renewable and distributed generation unit.

There are other reasons why it is necessary to store large amounts of energy. Depending on how storage is distributed, it may also help the network withstand peaks in demand. Storing energy allows transmission and distribution to operate at full capacity, decreasing the demand for newer or upgraded lines and increasing plant efficiencies. Storing energy for shorter periods may be useful for smoothing out small peaks and sags in voltage.

There is clearly a need for energy storage, specifically energy storage in a larger scale than before. Traditional energy storage methods, such as the electrochemical cell, are not necessarily applicable to larger-scale systems, and their efficiency may be suboptimal. Meanwhile, a number of new and promising methods are in development. Some of these are based on old concepts applied to modern energy storage, others are completely new ideas. Some are more mature than others, but most can be further improved.

In this work, an overview of the most important energy storage methods available or under development today is carried out. Clearly, the technologies and underlying principles for each storage method can vary to a large extend, thus diversifying significantly the spectrum of available energy storage products. This means that each method can be quite different in terms of its ideal application environment and energy storage scale. More specifically, while one method of storage may be ideal to smooth out annual fluctuations, another may be suitable to satisfy very short peak power requirements. Finally, where applicable, comparisons between the different methods are undertaken, in order to provide a basic understanding of the differences of each technology.

In Section 2, the flywheel technologies are presented and, in Section 3, the battery storage technologies are discussed. In Section 4, the supercapacitor storage technologies are illustrated and in Section 5 the hydrogen storage technologies are presented. The pneumatic storage technologies are presented in Section 6 and the pumped storage technology is discussed in Section 7. The conclusions are summarized in Section 8.

2. Flywheel storage technologies

A flywheel is a mass rotating about an axis, which can store energy mechanically in the form of kinetic energy. Energy is required to accelerate the flywheel so it is rotating. This is usually achieved by an electric motor when being used in an electrical system. Once it is rotating, it is in effect a mechanical battery that has a certain amount of energy that can be stored depending on its rotational velocity and its moment of inertia. The faster a flywheel rotates the more energy it stores. This stored energy can be retrieved by slowing down the flywheel via a decelerating torque and returning the kinetic energy to the electrical motor, which is used as a generator.

Apart from the rotating flywheel, the other main components of a flywheel storage system are the rotor bearings and the power interface as illustrated in Fig. 1 [5]. The flywheel can be either low speed, with operating speeds up to 6000 rpm, or high-speed with operating speeds up to 50,000 rpm [2]. Low speed flywheels are usually made of steel rotors and conventional bearings. Typical specific energy achieved is around 5 Wh/kg. High-speed flywheels use advanced composite materials for the rotor with ultra-low friction bearing assemblies. These light-weight and high-strength composite rotors can achieve specific energy of 100 Wh/kg. Also, such flywheels come up to speed in a matter of minutes, rather than the hours needed to recharge a battery. The container for high-speed flywheels is evacuated or helium filled to reduce aerodynamic losses and rotor stresses.

The power interface includes the motor/generator, a variable-speed power electronics converter and a power controller. The motor/generator is usually a high-speed permanent magnet machine integrated with the rotor functioning as an integrated synchronous generator. The converter is usually a pulse width modulated bi-directional converter which can be single-stage (ac to dc) or double-stage (ac to dc to ac) depending on the application requirements. Finally, a power controller is required to control power system variables.

The main advantages of flywheel storage systems are the high charge and discharge rates for many cycles. Indeed, the high cycling capability of flywheels is one of their key features and is not dependent on the charge or discharge rate. Full-cycle lifetimes range from 10^5 up to 10^7. In fact, the limiting factor in some applications is more likely to be the flywheel lifetime which is quoted as typically 20 years. Also, typical state-of-the-art composite rotors have high specific energies, up to 100 Wh/kg, with high specific power. Their

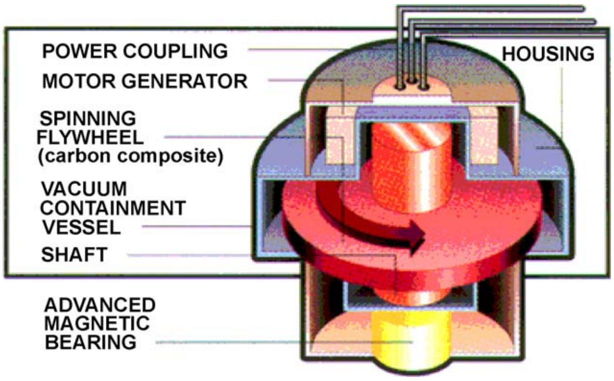

Fig. 1. Main components of a flywheel storage system [5].

energy efficiency is typically around 90% at rated power. The main disadvantages of flywheels are the high-cost and the relatively high standing losses. Self-discharge rates for complete flywheel systems are high, with minimum rate of 20% of the stored capacity per hour. These high rates have the effect of deteriorating energy efficiency when cycling is not continuous, for example when energy is stored for a period between charge and discharge. Such high discharge rates reinforce the notion that flywheels are not an adequate device for long-term energy storage but only to provide reliable standby power.

Such applications can be the integration of a flywheel energy storage system with a renewable energy source power plant system [12]. The amount of power produced by renewable energy sources such as photovoltaic cells and wind turbines varies significantly on an hourly, daily and seasonal basis due to the variation in the availability of the sun, wind and other renewable resources. Even when conventional technologies are generating electricity at a constant rate, there are demand fluctuations throughout the day. This mismatch of load to electrical supply means that power is not always available when it is required and on other occasions, there is excess power. Flywheel technologies can be used to provide power when there is insufficient power being generated, and to store excess production [5]. Another important application for flywheel technologies is for power conditioning and for providing power when there are durations of total power loss as a result of electricity grid failure.

3. Battery storage technologies

Storage batteries are rechargeable electrochemical systems used to store energy. They deliver, in the form of electric energy, the chemical energy generated by electrochemical reactions. These reactions are set in train inside a basic cell, between two electrodes plunged into an electrolyte, when a load is connected to the cell's terminals. The reaction involves the transfer of electrons from one electrode to the other through an external electric circuit/load.

A battery consists of single or multiple cells, connected in series or in parallel or both depending on the desired output voltage and capacity. Each cell, shown in Fig. 2, consists of:

- The anode or negative electrode which provides electrons to the load and is oxidised during the electrochemical reaction.
- The cathode or positive electrode which accepts electrons and is reduced during the reaction.
- The electrolyte which provides the medium for transfer of electrons between the anode and the cathode.
- The separators between positive and negative electrodes for electrical insulation.

There are three main types of conventional storage batteries that are used extensively today: the lead–acid batteries, the nickel-based batteries and the lithium-based batteries. Lead–acid batteries are the oldest type of rechargeable batteries and are based on chemical reactions involving lead dioxide (which forms the cathode electrode), lead (which forms the anode electrode) and sulphuric acid which acts as the electrolyte. The rated voltage of a lead–acid cell is 2 V and typical energy density is around 30 Wh/kg with power density around 180 W/kg [2]. Lead–acid batteries have high energy efficiencies (between 85 and 90%), are easy to install and require relatively low level of maintenance and low investment cost. In addition, the self-discharge rates for this type of batteries are very low, around 2% of rated capacity per month (at

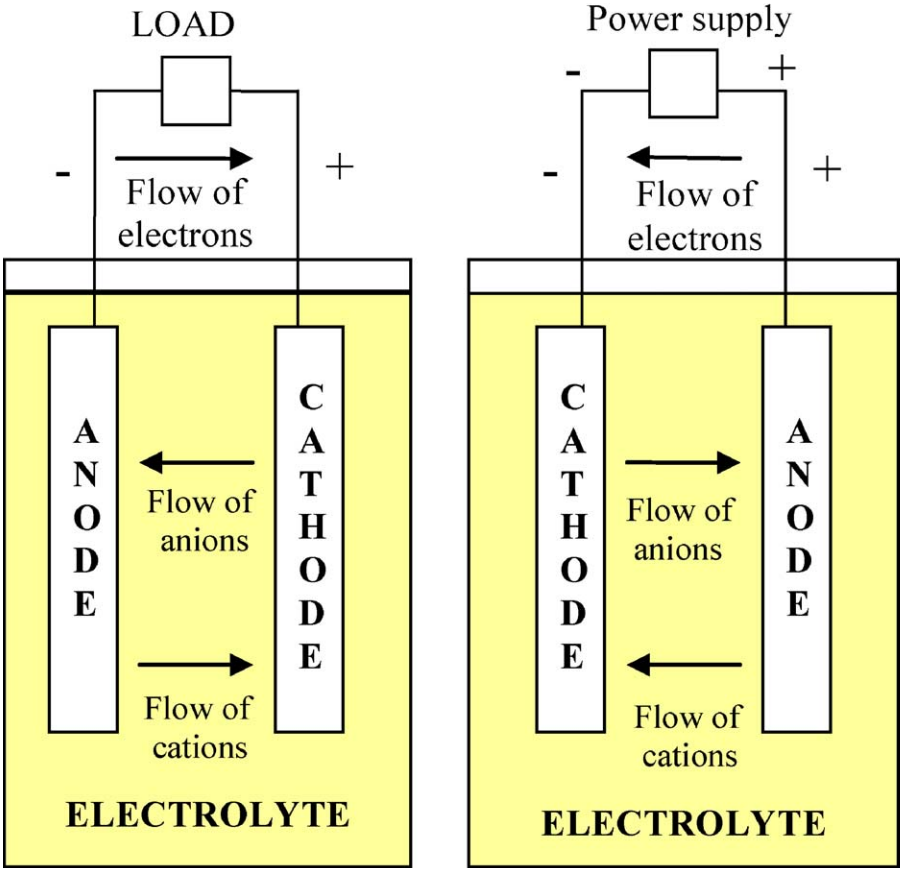

Fig. 2. Chargeable cell/battery diagram.

25 °C) which makes them ideal for long-term storage applications. However, the limiting factors for these batteries are the relatively low cycle life and battery operational lifetime. Typical lifetimes of lead–acid batteries are between 1200 and 1800 charge/discharge cycles or 5–15 years of operation. The cycle life is negatively affected by the depth of discharge and temperature. Attempts to fully discharge the battery can be particularly damaging to the electrodes, thus reducing lifetime. Regarding temperature levels, although high temperatures (up to 45 °C which is the upper limit for battery operation) may improve battery performance in terms of higher capacity, they can also reduce total battery lifetime as well as the battery energy efficiency.

The nickel-based batteries are mainly the nickel–cadmium (NiCd), the nickel–metal hydride (NiMH) and the nickel–zinc (NiZn) batteries. All three types use the same material for the positive electrode and the electrolyte which is nickel hydroxide and an aqueous solution of potassium hydroxide with some lithium hydroxide, respectively. As for the negative electrode, the NiCd type uses cadmium hydroxide, the NiMH uses a metal alloy and the NiZn uses zinc hydroxide. The rated voltage for the alkaline batteries is 1.2 V (1.65 V for the NiZn type) and typical maximum energy densities are higher than for the lead–acid batteries. Typically, values are 50 Wh/kg for the NiCd, 80 Wh/kg for the NiMH and 60 Wh/kg for the NiZn. Typical operational life and cycle life of NiCd batteries is also superior to that of the lead–acid batteries. At deep discharge levels, typical lifetimes for the NiCd batteries range from 1500 cycles for the pocket plate vented type to 3000 cycles for the sinter vented type. The NiMH and NiZn have similar or lower values to those of the lead–acid batteries.

Despite the above advantages of the NiCd batteries over the lead–acid batteries, NiCd and the rest of the nickel-based batteries have several disadvantages compared to the lead–acid batteries in terms of industrial use or for use in supporting renewable energy power systems. Generally, the NiCd battery is the only one of the three types of nickel-based batteries that is commercially used for industrial UPS applications such as in large energy storage for renewable energy systems. However, the NiCd battery may cost up to 10 times more than the lead–acid battery. On top of that, the energy efficiencies for the nickel batteries are lower than for the lead–acid batteries. The NiMH batteries have energy efficiencies between 65 and 70% while the NiZn have 80% efficiency. The energy efficiency of the NiCd batteries varies depending on the type of technology used during manufacture. For the vented type, the pocket plate have 60%, the sinter/PBE plate have 73%, the fibre plate 83% and the sinter plate have 73% energy efficiency. Finally, the sealed cylindrical type of NiCd batteries has 65% energy efficiency. Another dimension where the NiCd batteries are inferior to the lead–acid batteries is the self-discharge rate. Self-discharge rates for an advanced NiCd battery are much higher than those for a lead–acid battery since they can reach more than 10% of rated capacity per month.

The third major type of battery storage technology is the lithium-based battery storage system. This technology has not yet been used for energy storage in the context of an uninterrupted power supply (UPS) system although such applications are being developed. Currently, lithium battery technology is typically used in mobile or laptop systems and in the near future it is envisaged to be used in hybrid or electric vehicles. Lithium technology batteries consist of two main types: lithium-ion and lithium-polymer cells. Their advantage over the NiCd and lead–acid batteries is their higher energy density and energy efficiency, their lower self-discharge rate and extremely low maintenance required. Lithium-ion cells, with nominal voltage around 3.7 V, have energy densities ranging from 80 to 150 Wh/kg while for lithium-polymer cells it ranges from 100 to 150 Wh/kg. Energy efficiencies range from 90 to 100% for both these technologies. Power density for lithium-ion cells ranges from 500 to 2000 W/kg while for lithium-polymer it ranges from 50 to 250 W/kg.

For lithium-ion batteries, self-discharge rate is very low at maximum 5% per month and battery lifetime can reach more than 1500 cycles. However, the lifetime of a lithium-ion battery is temperature dependent, with aging taking its toll much faster at high temperatures, and can be severely shortened due to deep discharges. This makes lithium-ion batteries unsuitable for use in back-up applications where they may become completely discharged. In addition, lithium-ion batteries are fragile and require a protection circuit to maintain safe operation. Built into each battery pack, the protection circuit limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge. In addition, the cell temperature is monitored to prevent temperature extremes. The maximum charge and discharge current on most packs are also limited. These precautions are necessary in order to eliminate the possibility of metallic lithium plating occurring due to overcharge.

Lithium-polymer battery lifetime can only reach about 600 cycles. Regarding its self-discharge, this is much dependent on temperature but it has been reported to be around 5% per month. Compared to the lithium-ion battery, the lithium-polymer battery operational specifications dictate a much narrower temperature range, avoiding lower temperatures. However, lithium-polymer batteries are lighter, and safer with minimum self-inflammability.

Currently research into lithium-based batteries is mainly concerned with cost reduction by use of cheaper materials, lifetime

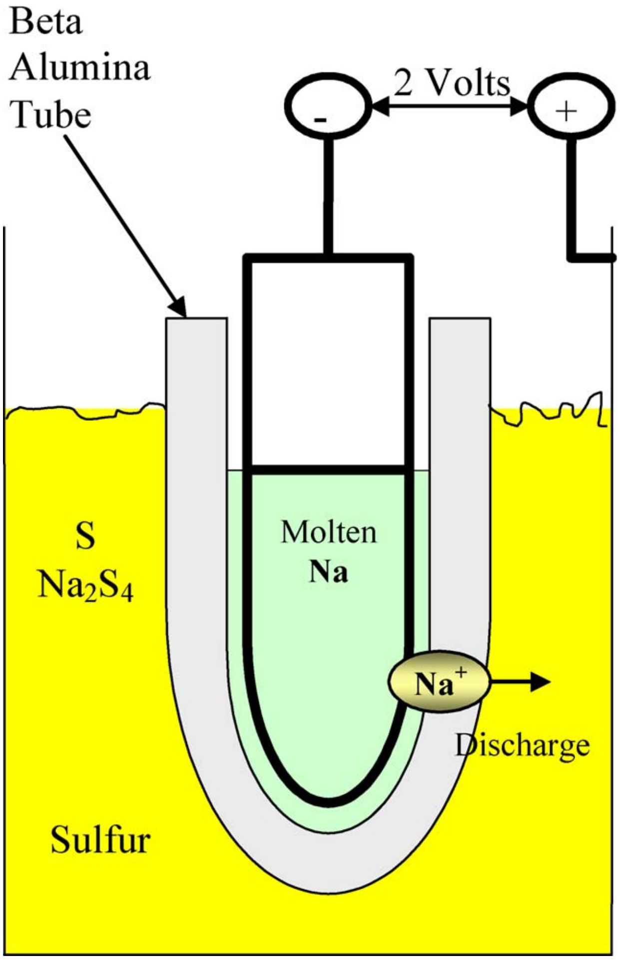

Fig. 3. Basic 2 V NaS cell/battery operation.

increase and reduction of high flammability, especially in the case of lithium-ion batteries. Cost is currently estimated to be between 900 and 1300$/kWh.

Apart from the three main types of batteries described above, a few additional types also exist albeit with low penetration in the market. These are the sodium sulphur (NaS) battery, the Redox flow storage system and the metal–air battery.

The NaS battery consists of liquid (molten) sulphur at the positive electrode and liquid (molten) sodium at the negative electrode as active materials separated by a solid beta alumina ceramic electrolyte as shown in Fig. 3. The electrolyte allows only the positive sodium ions to go through it and combine with the sulphur to form sodium polysulphides. During discharge, sodium gives off electrons, while positive Na^+ ions flow through the electrolyte and migrate to the sulphur container. The electrons flow in the external circuit of the battery producing about 2 V and then through the electric load to the sulphur container [11]. Here the electron reacts with the sulphur to form S^- cations, which then forms sodium polysulphide after reacting with sodium ions. As the cell discharges, the sodium level drops. This process is reversible as charging causes sodium polysulphides to release the positive sodium ions back through the electrolyte to recombine as elemental sodium. Once running, the heat produced by charging and discharging cycles is enough to maintain operating temperatures and no external heat source is required to maintain this process. Heat produced is typically about 300–350 °C.

NaS batteries are highly energy efficient (89–92%) and are made from inexpensive and non-toxic materials. However, the high operating temperatures and the highly corrosive nature of sodium make them suitable only for large-scale stationary applications. NaS batteries are currently used in electricity grid related applications such as peak shaving and improving power quality.

Finally, the two other emerging battery storage technologies that are currently not yet used on a commercial basis are the metal–air energy storage system and the Redox flow storage system. Both these technologies are under continuous research and technological development so as to become commercialized. Redox technology offers significant advantages such as no self-discharge and no degradation for deep discharge but it still faces technical development issues and also requires high investment cost. Metal–air technology offers high energy density (compared to lead–acid batteries), and long shelf life while promising reasonable cost levels. However, tests have shown that the metal–air batteries suffer from limited operating temperature range and a number of other technical issues not least of which is the difficulty in developing efficient, practical fuel management systems and cheap and reliable bifunctional electrodes.

4. Supercapacitor storage technologies

Supercapacitors (or ultracapacitors) are very high surface areas activated capacitors that use a molecule-thin layer of electrolyte as the dielectric to separate charge. The supercapacitor resembles a regular capacitor except that it offers very high capacitance in a small package. Supercapacitors rely on the separation of charge at an electric interface that is measured in fractions of a nanometer, compared with micrometers for most polymer film capacitors. Energy storage is by means of static charge rather than of an electro-chemical process inherent to the battery [2].

Depending on the material technology used for the manufacture of the electrodes, supercapacitors can be categorized into electrochemical double layer supercapacitors (ECDL) and pseudo-capacitors. Hybrid capacitors are also a new category of supercapacitors (see Fig. 4 for supercapacitor taxonomy). ECDL supercapacitors are currently the least costly to manufacture and are the most common type of supercapacitor.

The main components of an ECDL supercapacitor can be observed in Fig. 5. The ECDL supercapacitors have a double-layer construction consisting of carbon-based electrodes immersed in a liquid electrolyte (which also contains the separator) [13]. As electrode material, porous active carbon is usually used. Recent technological advancements have allowed carbon aerogels and carbon nanotubes to also be employed as electrode material. The electrolyte is either organic or aqueous. The organic electrolytes use usually acetonitrile and allow nominal voltage of up to 3 V. Aqueous electrolytes use either acids or bases (H_2SO_4, KOH) but the nominal voltage is limited to 1 V. During charging, the electrically charged ions in the electrolyte migrate towards the electrodes of opposite polarity due to the electric field between the charged electrodes created by the applied voltage. Thus two separate charged layers are produced. Although, similar to a battery, the double-layer capacitor depends on electrostatic action. Since no chemical action is involved the effect is easily reversible with minimal degradation in deep discharge or overcharge and the typical cycle life is hundreds of thousands of cycles. Reported cycle life is more than 500,000 cycles at 100% depth of discharge. The limiting factor in terms of lifetime may be the years of operation with reported lifetimes reaching up to 12 years. Another limiting

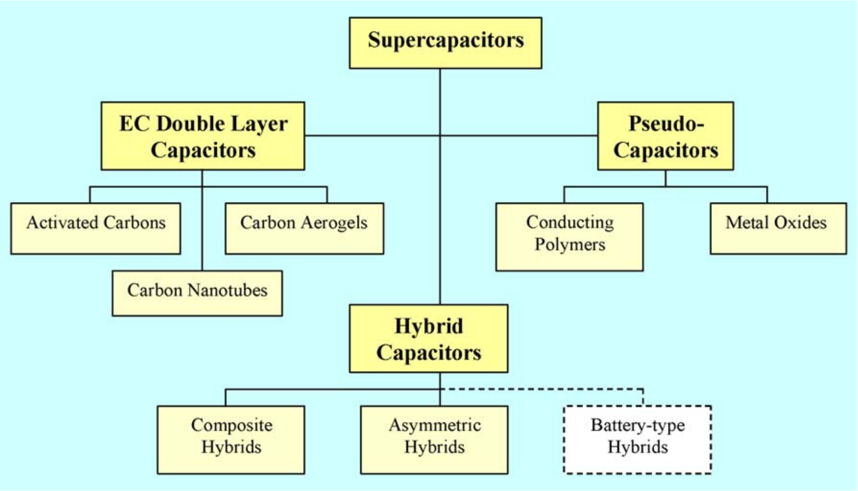

Fig. 4. Taxonomy of supercapacitors.

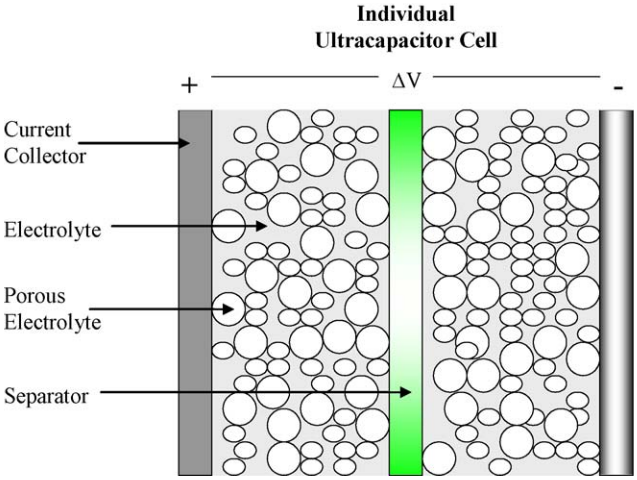

Fig. 5. ECDL supercapacitor cell.

factor is the high self-discharge rate of supercapacitors. This rate is much higher than batteries reaching a level of 14% of nominal energy per month [2]. Apart from high tolerance to deep discharges, the fact that no chemical reactions are involved means that supercapacitors can be easily charged and discharged in seconds thus being much faster than batteries. Also, no thermal heat or hazardous substances can be released during discharge. Energy efficiency is very high, ranging from 85% up to 98%.

Compared to conventional capacitors, the supercapacitors have significantly larger electrode surface area coupled with much thinner electrical layer between the electrode and the electrolyte. The layer's thickness is only a few molecular diameters. These two attributes mean that supercapacitors have higher capacitances and therefore energy densities than conventional capacitors. Capacitances of 5000 F have been reported with supercapacitors and energy densities up to 5 Wh/kg compared to 0.5 Wh/kg of conventional capacitors. Current currying capability of the supercapacitors is also very high since it is directly proportional to the surface area of the electrodes. Thus, power density of supercapacitors is extremely high, reaching values such as 10,000 W/kg which is a few orders of magnitude higher than the power densities achieved with batteries. However, due to the low energy density, this high amount of power will only be available for a very short duration. In the cases where supercapacitors are used to provide power for prolonged periods of time, it is at the cost of considerable added weight and bulk of the system due to their low energy density.

Supercapacitor cost is a significant issue for the further commercial use of supercapacitors in industrial applications. Cost, which is estimated to be around 20,000$/kWh, is significantly higher compared to well-established storage technologies such as lead–acid batteries. Drastic cost reduction must therefore be accomplished especially in the carbon, electrolyte and separator fields. Currently, the high power storage ability of supercapacitors together with the fast discharge cycles, make them ideal for use in temporary energy storage for capturing and storing the energy from regenerative braking and for providing a booster charge in response to sudden power demands. At the same time, supercapacitors can provide effective short duration peak power boost, and short-term peak power back up for UPS applications. By combining a supercapacitor with a battery-based UPS system, the life of the batteries can be extended by load sharing between battery and supercapacitor. The batteries provide power only during the longer interruptions, reducing the peak loads on the battery and permitting the use of smaller batteries.

Currently developments in supercapacitor manufacturing technology have shown that the use of vertically aligned, single-wall carbon nanotubes which are only several atomic diameters in width instead of the porous, amorphous carbon normally employed can significantly increase the supercapacitor capacity and power density. This is due to the fact that the surface area of the electrodes is dramatically increased by the use of such materials. Energy densities of 60 Wh/kg and power densities of 100,000 W/kg can be achieved with this technology.

Pseudo-capacitors and hybrid capacitors are also promising technologies because they can achieve improved performances where ECDL supercapacitors offered inferior capabilities. Pseudo-capacitors use metal oxides or conducting polymers as electrode material and can achieve higher energy and power densities than ECDL supercapacitors. Metal-oxide supercapacitors use aqueous electrolytes and metal oxides such as ruthenium oxide (RuO_2), iridium oxide and nickel oxide mainly for military applications. These supercapacitors are based on a high kinetics charge transfer at the electrode/electrolyte interface transforming ruthenium oxide into ruthenium hydroxide ($Ru(OH)_2$) leading to pseudo-capacitive behaviour. Metal-oxide supercapacitors are however still very expensive to produce and may suffer from lower efficiencies and lower voltage potential due to the need for aqueous electrolytes. Hybrid supercapacitors can reach even higher energy and power densities than the other supercapacitors without sacrifices in affordability or cyclic stability. They are however still a new and unproven technology and still require more research to better understand and realise their full potential [4].

5. Hydrogen storage technologies

Currently there are four main technologies for hydrogen storage out of which two are more mature and developed. These are the hydrogen pressurization and the hydrogen adsorption in metal hydrides. The remaining two technologies that are still in research and technological development phase are the adsorption of hydrogen on carbon nanofibres and the liquefaction of hydrogen.

Pressurized hydrogen technology relies on high materials permeability to hydrogen and to their mechanical stability under pressure. Currently steel tanks can store hydrogen at 200–250 bar but present very low ratio of stored hydrogen per unit weight. Storage capability increase with higher pressures but stronger materials are then required. Storage tanks with aluminium liners and composite carbon fibre/polymer containers are being used to store hydrogen at 350 bar providing higher ratio of stored hydrogen per unit weight (up to 5%). In order to reach higher storage capability, higher pressures are required in the range of 700 bar with the unavoidable auxiliary energy requirements for the compression. Research is currently under way to materials that are adequate for use in such high pressures [2].

The use of metal hydrides as storage mediums is based on the excellent hydrogen absorption properties of these compounds. These compounds, obtained through the direct reaction of certain metals or metal alloys to hydrogen, are capable of absorbing the hydrogen and restoring it when required. These compounds have a low equilibrium pressure at room temperature (lower than atmospheric pressure) in order to prevent leaks and guarantee containment integrity and a low degree of sensitivity to impurities in the hydrogen stored. The use of such a storage technology is safe, as the pressure remains low, and it is compact because most hydrides have high volume absorption capacities (ratio of the volume of hydrogen stored to the volume of metal used) [1]. An example of metal hydride containers is shown in Fig. 6 [6]. However, metal hydride compounds have some disadvantages.

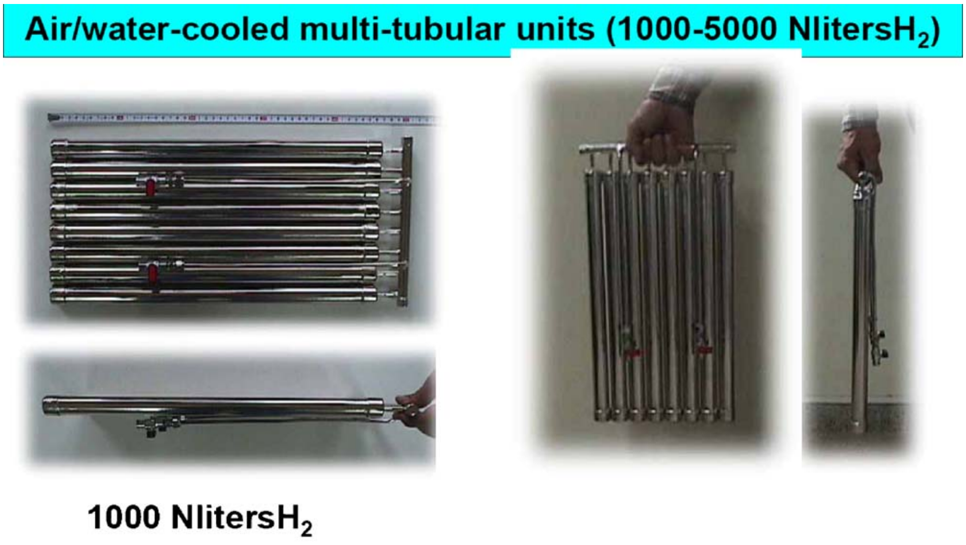

Fig. 6. Air/water-cooled multi-tubular metal hydride storage units [6].

Typically, they exhibit rather low mass absorption capacities (except magnesium hydrides) and do require thermal management system. This is because the absorption of hydrogen is an exothermic reaction (releases heat) while desorption of hydrogen is endothermic. Heating and cooling of the metal hydrides containers is achieved via the use of water running through pipework in the interior of the container. Absorption/desorption kinetics are however very fast in most hydrides thus allowing for fast hydrogen storage and release. Materials most often employed in this hydrogen storage technology are seldom earth materials such as lanthanum, and other materials such as nickel and aluminium.

Liquid hydrogen storage technology use is currently limited. This is due to the properties and cost of the materials used in the manufacturing of the container/tank and the extreme temperatures that are required for such storage. The typical temperature required to maintain hydrogen in a liquid state is around $-253\ ^{\circ}\mathrm{C}$. Storage containers have to use specific internal liner surrounded by a thermal insulator in order to maintain the required temperature and avoid any evaporation. The whole process is quite inefficient since a lot of energy is used already in the initial stage of hydrogen liquefaction. In addition, liquid hydrogen tanks suffer from leaks (escaping hydrogen flow) due to the unavoidable thermal losses that lead to pressure increase in the tank. This hydrogen self-discharge of the tank may reach 3% daily which translates to 100% self-discharge in 1 month.

Finally, the use of carbon nanofibres for hydrogen storage is in its initial research stage. Different materials are still under investigation as to their storage potential depending on the temperature and pressure of the hydrogen.

6. Pneumatic storage technologies

Pneumatic storage technologies can use either compressed air or compressed gas to achieve energy storage. In compressed gas applications, a system similar to a hydraulic accumulator is employed which can store and release energy through its integration with a motor/generator and a pump/motor. A hydraulic accumulator is a pressure storage device made up of a reservoir in which a non-compressible hydraulic fluid is held under pressure by compressed gas. This technology is typically referred to as “Battery with Oil-Hydraulics and Pneumatics” or BOP. Compressed air applications are able to store energy on a much bigger scale and are used under the abbreviation CAES (compressed air energy storage). In this type of storage technology, air is stored in pre-specified underground locations and released under pressure to a drive the gas turbines of the electricity generation plant. Both these technologies are explained briefly below.

6.1. Liquid-piston technology

This technology is based on a compressed gas hydraulic accumulator together with the addition of a pump/motor and a motor/generator as shown in Fig. 7. This technology provides an almost perfect isothermal behaviour due to the low speed of the compression/expansion process which is distributed over all the storage vessels and hence linked to an enormous heat exchange surface.

The basic principle of operation is that compression and expansion of a trapped volume of gas – usually nitrogen – (see Fig. 7) take place in a storage vessel and its volume and pressure are modulated by the amount of fluid/liquid in the vessel. Gas pressures vary from 100 bar (no fluid present) to 250 bar (50% of the vessel filled with fluid). During energy storage, the high-efficiency fixed displacement pump/motor is energized by the electrical machine or motor/generator and acts as a pump

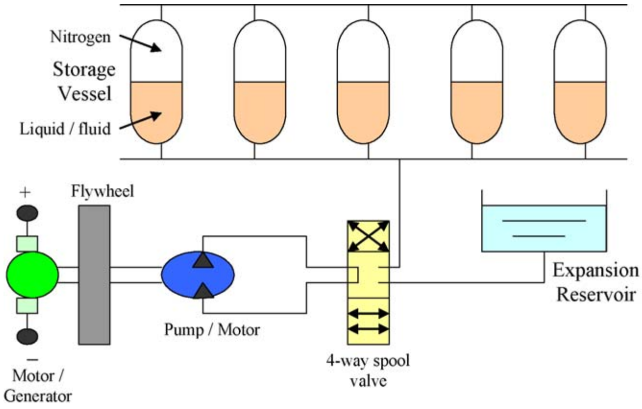

Fig. 7. Basic arrangement for the liquid-piston electric power technology [2].

compressing the gas in the accumulator vessels with the fluid. During discharge of energy, the compressed gas is expanded and fluid is expelled from the vessels to the pump/motor which acts now as a motor to drive the electrical machine as a generator of electric power. To complete the system, a solenoid powered 4-way spool valve is used which works in conjunction with a flywheel, designed to maintain a low-rippled speed for the motor/generator. A fluid expansion reservoir is also necessary.

This technology is not yet on a commercial basis, but it is hoped that it can initially substitute the lead–acid batteries in certain stand-alone stationary equipment applications. The first targeted applications are systems with drives mainly for workshops, food processing, milking and UPS installations. In these types of applications, its performance can compete with the performance of lead–acid batteries although this technology remains more expensive. Pneumatic storage technology's main advantages over the lead–acid batteries are (a) unlimited cycling ability and lifetime since cycling is not dependent on charge/discharge profiles, (b) lower maintenance required, (c) storage capacity not affected by age or speed of charge, (d) undamaged performance in cases of full discharge, (e) overcharge is impossible, as the system is protected by a relief valve in the hydraulic circuit, (f) free of charge regulators and low voltage cut-off switches, (g) power supply is not linked to capacity and it is limited only by the transformer design characteristics and (h) self-discharge at open circuit (tightly closed circuit valve, shut-off system) is almost zero allowing for many years of operation.

Some disadvantages of the above technology compared to the lead–acid batteries are (a) energy density is lower and ranges from 3.2 to 5.55 Wh/kg (250 bar pressure), in fact energy density increases with pressure, however there is limitation to the maximum pressure that is bearable by the hydraulic system components and materials, (b) although self-discharge is almost zero at tightly closed valve, there is considerable self-discharge at voltage standby mode which presents an operational limitation (applications with long shut-off periods, such as seasonal systems, are therefore a more adequate target for pneumatic storages), (c) the chance of possible leakage in the pneumatic and hydraulic piping that needs to be monitored and fixed and (d) energy efficiency is slightly lower to a new lead–acid battery, at around 73% (efficiency level is projected to increase by the advancements in research and by the continuous technological developments in this technology).

6.2. Compressed air energy storage

In CAES, off-peak power is taken from the grid and is used to pump air into a sealed underground cavern to a high pressure. The pressurized air is then kept underground for peak use. When needed, this high pressure can drive turbines as the air in the cavern is slowly heated and released. The resulting power may be used at peak hours.

There are many geologic formations that can be used in this used in this scheme. These include naturally occurring aquifers, solution-mined salt caverns and constructed rock caverns. In general, rock caverns are about 60% more expensive to mine than salt caverns for CAES purposes. This is because underground rock caverns are created by excavating solid rock formations, whereas salt caverns are created by solution mining of salt formations [10].

Aquifer storage is by far the least expensive method and is therefore used in most of the current locations. The other approach to compressed air storage is called CAS, compressed air storage in vessels. In a CAS system, air is stored in fabricated high-pressure tanks. However, the current technology is not advanced enough to manufacture these high-pressure tanks at a feasible cost. The scales proposed are also relatively small compared to CAES systems.

There are five aboveground components required by a basic CAES installation as shown in Fig. 8:

- The motor/generator which employs clutches to provide for alternate engagement to the compressor or turbine trains.
- The air compressor which may require two or more stages, intercoolers and aftercoolers to achieve economy of compression, and reduce the moisture content.
- The recuperator, turbine train, high and low pressure turbines.
- Equipment control centre for operating the combustion turbine, compressor, and auxiliaries and to regulate and control change-over from generation mode to storage mode.
- Auxiliary equipment consisting of fuel storage and handling, and mechanical and electrical systems to support various heat exchangers required.

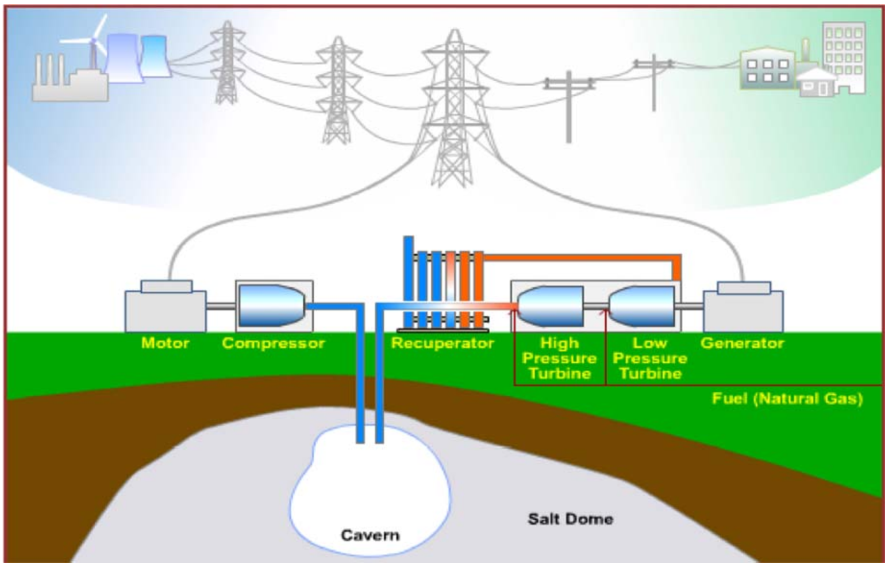

Fig. 8. Basic components for a CAES system [10].

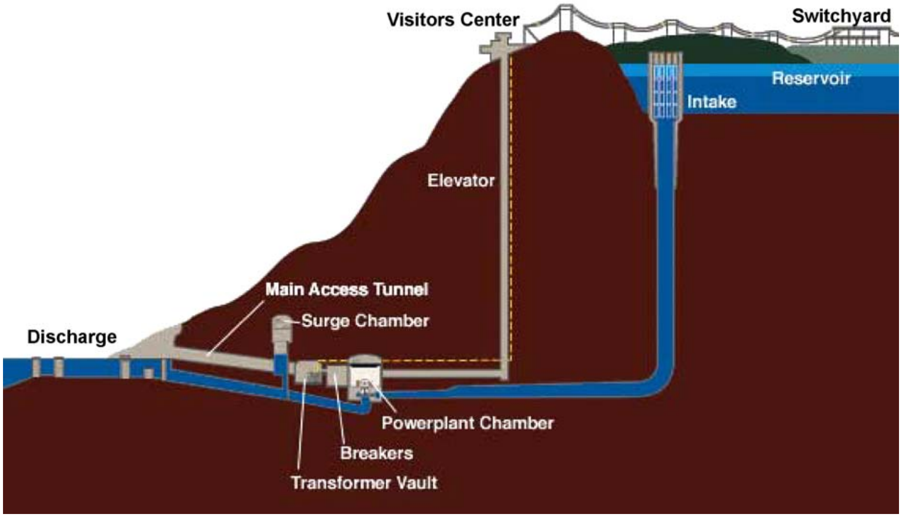

Fig. 9. A typical pumped storage plant [10].

A CAES operates by means of large electric motor driven compressors that store energy in the form of compressed air in the mine. The compression is done outside periods of peak demand. As part of the compression process, the air is cooled prior to injection to make the best possible use of the storage space available. The air is then pressurized to about 75 bar. To return electricity to the consumers, air is extracted from the cavern. It is first preheated in the recuperator. The recuperator reuses the energy extracted by the compressor coolers. The heated air is then mixed with small quantities of oil or gar, which is burnt in the combustor. The hot gas from the combustor is expanded in the turbine to generate electricity.

CAES systems can only be used on very large scales. Unlike other systems considered large-scale, CAES is ready to be used with entire power plants. Apart from the hydro-pump, no other storage method has a storage capacity as high as CAES. Typical capacities for a CAES system are around 50–300 MW. The storage period is also the longest due to the fact that the losses are very small. A CAES system can be used to store energy for more than a year.

Fast start-up is also an advantage of CAES. A CAES plant can provide a start-up time of about 9 min for an emergency start, and about 12 min under normal conditions. By comparison, conventional combustion turbine peaking plants typically require 20–30 min for a normal start-up.

If a natural geological formation is used (rather than CAS), CAES has the advantage that it does not involve huge, costly installations. Moreover, the emission of greenhouse gases is substantially lower than in normal gas plants.

The main drawback of CAES is probably the geological structure reliance. There is actually not a lot of underground cavern around, which substantially limits the usability of this storage method. However, for locations where it is suitable, it can provide a viable option for storing energy in large quantities and for long times.

7. Pumped storage technology

Pumped storage hydroelectricity is a method of storing and producing electricity to supply high peak demands by moving water between reservoirs at different elevations.

At times of low electricity demand, excess generation capacity is used to pump water into the higher reservoir (Fig. 9). When there is higher demand, water is released back into the lower reservoir through a turbine, generating electricity. Reversible turbine/generator assemblies act as pump and turbine. Some facilities use abandoned mines as the lower reservoir, but many use the height difference between two natural bodies of water or artificial reservoirs. Pure pumped storage plants just shift the water between reservoirs, but combined pump-storage plants also generate their own electricity like conventional hydroelectric plants through natural steam-flow. Plants that do not use pumped storage are referred to as conventional hydroelectric plants.

Taking into account evaporation losses from the exposed water surface and conversion losses, approximately 70–85% of the electrical energy used to pump the water into the elevated reservoir can be regained. The technique is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis, but capital costs and the presence of appropriate geography are critical decision factors.

The relatively low energy density of pumped storage systems requires either a very large body of water or a large variation in height. The only way to store a significant amount of energy is by having a large body of water located on a hill relatively near, but as high as possible above a second body of water. In some places this occurs naturally, in others one or both bodies of water have been man-made.

Pumped storage system may be economical because it flattens out load variations on the power grid, permitting thermal power stations such as coal-fired plants and nuclear plants that provide base-load electricity to continue operating at peak efficiency, while reducing the need for peaking power plants that use costly fuels. Capital costs for purpose-build hydro storage are high, however.

Along with energy management, pumped storage systems help control electrical network frequency and provide reserve generation. Thermal plants are much less able to respond to sudden changes in electrical demand, potentially causing frequency and voltage instability. Pumped storage plants, like other hydroelectric plants, can respond to load changes within seconds.

8. Conclusions

A comparison of the main attributes of three important power storage technologies is presented in Table 1. Flywheel storage technology is compared to the lead–acid and the nickel–cadmium battery technologies [8,2,9]. It is clear from this table that conventional flywheel technology (with steel rotor) differs substantially from battery technology. Although conventional flywheel technology can provide much higher deep-cycle life and therefore more charge-discharge cycles in a storage application,

Table 1
Comparison among three prominent energy storage systems.

Parameter	Lead–acid battery	Flywheel technology	Nickel–cadmium battery
Storage mechanism	Chemical	Mechanical	Chemical
Life (years in service)	3–12	>20	15–20
Life (deep cycles)	<1500 cycles	$<10^7$ cycles	<3000 cycles
Self-discharge rate	Very low	Very high	Very low
Technology	Proven	Promising (proven)	Proven
Tolerance of overcharge & deep-discharge	Very low	High	Low
Environmental concerns	Chemical disposal issues	Slight	Chemical disposal issues
Energy density	30 Wh/kg	5 Wh/kg steel 100 Wh/kg composite	15–50 Wh/kg
Power density	180 W/kg	1000 W/kg composite	50–1000 W/kg
Price/kWh	$50–100	$400–800	$400–2400

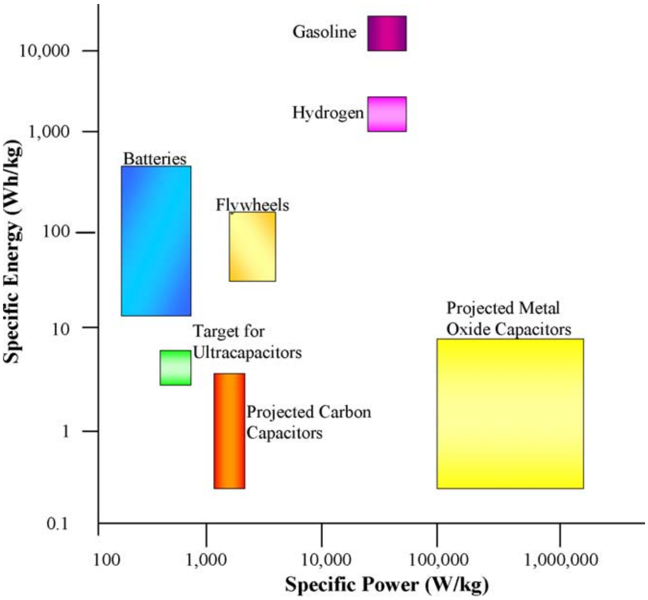

Fig. 10. Comparison of specific power and energy storage potential of each storage technology [7].

its much higher self-discharge rate is still prohibitive for large-scale penetration of flywheel technology. In contrast to a battery, conventional flywheel technology can be used for high power density storage applications, while batteries are only suited to high energy storage applications. However, the newly evolving composite rotor flywheel technology promises higher energy densities comparable to the levels achieved with batteries. Finally in terms of investment cost, flywheel technology incurs higher costs due to the fact that the technology is still at a relatively early stage in its lifecycle compared to traditional battery technologies such as lead–acid or nickel–cadmium batteries.

The deliverable power and energy that can be provided by the majority of the storage technologies discussed so far can be shown in Fig. 10. In this figure, a comparison is presented in terms of energy and power density achievable with each technology. Fig. 7 confirms that batteries have the lowest power density, and the highest energy density (with the exception of hydrogen storage technologies). The evolving metal-oxide supercapacitors are shown to be able to achieve the highest possible power densities. Compressed air energy storage and pumped storage technologies are not shown in Fig. 7, since the scale of power applications suitable for these technologies far exceeds the scale of the chart. Typical power applications for these technologies are in the order of 100 of MW.

From the above analysis, it is clear that a large variety of storage technologies exists with each one possessing different attributes and intended for different applications. The choice of the ideal storage technology to be used depends on a number of factors. These are, among others, the amount of energy or power to be stored, the time for which this stored energy is required to be retained or to be released, spacing and environmental constraints, cost, and the exact location of the network on which the storage is required.

It is evident from the above review that batteries are the dominant technology to be used when continuous energy supply is paramount, while technologies such as flywheel and super-capacitors are more suited to power storage applications and where very brief power supply is required such as in uninterrupted power supply requirements. Lithium-ion batteries are becoming increasingly important and have several advantages over the traditional lead–acid batteries. Fuel cells performance is constantly improving in terms of reliability and investment cost, while some types (e.g. SOFC) can provide very high efficiencies in the context of combined heat and power (CHP) applications [3]. However, the future penetration of fuel cells remains tied to the high-cost hydrogen production and storage processes. Finally, pumped storage and CAES technologies are suited to very high power, high investment cost generation applications to be used in the transmission system.

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References

[1] Christodoulou C, Karagiorgis G, Poullikkas A, Karagiorgis N, Hadjiargyriou N. Green electricity production by a grid-connected H2/fuel cell in Cyprus. In: Proceedings of the Renewable Energy Sources and Energy Efficiency; 2007.
[2] Investigation on storage technologies for intermittent renewable energies: evaluation and recommended R&D strategy, INVESTIRE-NETWORK (ENK5-CT-2000-20336), Storage Technology Reports (http://www.itpower.co.uk).
[3] Poullikkas A. Implementation of distributed generation technologies in isolated power systems. Renewable and Sustainable Energy Reviews 2007;11:30–56.
[4] Supercapacitors and other nano-enabled energy systems, Marin Halper, MITRE Nanosystems Group; 2006 (http://www.mitre.org).
[5] http://www.activepower.com.
[6] http://www.hystoretechnologies.com.
[7] http://www.nrel.gov.
[8] http://www.cap-xx.com.
[9] Ibrahim H, Ilinca A, Perron J. Energy storage systems—characteristics and comparisons. Renewable and Sustainable Energy Reviews 2007;12:1221–50.
[10] http://www.doc.ic.ac.uk.
[11] http://www.electricitystorage.org.
[12] http://www.enercon.com.
[13] http://www.mpoweruk.com.