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Energy storage technologies and real life applications – A state of the art review

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HIGHLIGHTS

- Primary and secondary energy forms introduced.
- Different (electrical and thermal) energy storage technologies presented and compared.
- Real life energy storage application analysed to understand the most widely applied technology.
- Challenges facing the energy storage industry summarised.
- Future prospects of the energy storage sector predicted.

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ABSTRACT

Energy storage is nowadays recognised as a key element in modern energy supply chain. This is mainly because it can enhance grid stability, increase penetration of renewable energy resources, improve the efficiency of energy systems, conserve fossil energy resources and reduce environmental impact of energy generation. Although there are many energy storage technologies already reviewed in the literature, these technologies are currently at different levels of technological maturity with a few already proven for commercial scale application. Most of the review papers in energy storage highlight these technologies in details, however; there remains limited information on the real life application of these technologies for energy storage purpose. This review paper aims to address this gap by providing a detailed analysis of real life application and performance of the different energy storage technologies. The paper discusses the concept of energy storage, the different technologies for the storage of energy with more emphasis on the storage of secondary forms of energy (electricity and heat) as well as a detailed analysis of various energy storage projects all over the world. In the final part of this paper, some of the challenges hindering the commercial deployment of energy storage technologies are also highlighted.

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1. Introduction

Energy in whatever form is an essential commodity globally. It is the most common consumer good and has continued to be a key element to the worldwide development. Energy comes in various forms although it can be broadly classified into two [1]. They include: primary and secondary forms of energy. Primary energy are regarded as those energy sources that only involve extraction or capture, with or without separation from contiguous material, cleaning or grading, before the energy contained in it can be converted into heat or mechanical work [1]. They are usually found in nature. They include all energy forms which have not been subjected to any conversion or transformation process. Typical examples are crude oil, coal, biomass, wind, solar, tidal, natural uranium, geothermal, falling and flowing water, natural gas, etc. On the other hand, secondary forms of energy include all energy forms which occur as a result of the transformation of primary energy using energy conversion processes. Fig. 1 shows the relationship between the primary and secondary energy forms.

Secondary energy forms are more convenient forms of energy as they can directly be used by humankind. They are also known as Energy Carriers (EC). Examples of secondary energy forms are electricity, gasoline, diesel, ethanol, butanol, hydrogen, heat. Table 1 shows the different primary energy forms and the corresponding technology used to transform it to secondary energy form.

Cumulatively, energy consumption has been growing significantly over the years. According to the 2014 key world energy statistics released by the International Energy Agency (IEA), about 13,371 Mtoe of energy is supplied globally in 2012 [2]. This is about 10% and 119% higher than the 2009 and 1973 values respectively [3,4]. Although there is an increasing trend in the global energy supply, the percentage share of fossil fuel has been decreasing gradually due to the penetration of renewable energy systems. For example, approximately 82% of the primary energy supply in 2012 came from fossil fuels compared to 87% in 1973 [2]. However, this reduction in fossil fuels share in the primary energy supply does not portray in actual terms a reduction in CO_2 emission. For example, fossil fuels contributed about 31,734 Mt of CO_2 emissions in 2012 compared to 16,633 Mt in 1973 [2,4].

CO_2 emissions from fossil fuels have been identified as a major global environmental threat due to its contribution to global warming. For the past years, many efforts have been made to reduce CO_2 emission in order to mitigate the associated environmental impact. These range from creating new and innovative energy conversion technologies to improving the efficiency of existing energy conversion technologies. Furthermore, reducing energy wastage from a variety of industries whether domestic or commercial by storing them for future use has a very significant impact in reducing CO_2 emission. The need to balance the mismatch between energy supplied to the grid and the energy actually used from the grid by storing the excess energy is equally important to achieving a low carbon economy. It is against this backdrop that energy storage is believed to be essential in the modern energy supply chain as it will help to plug the leakages and improve efficiency. As a result of this, energy storage has recently attracted the attention of governments, stakeholders, researchers and investors as it may be used to improve the performance of the energy supply chain.

1.1. Motivations for energy storage

Energy storage is an essential link in energy supply chain. For example, it is a fact that there is no system that is 100% thermodynamically efficient. The energy losses in most systems occur in the

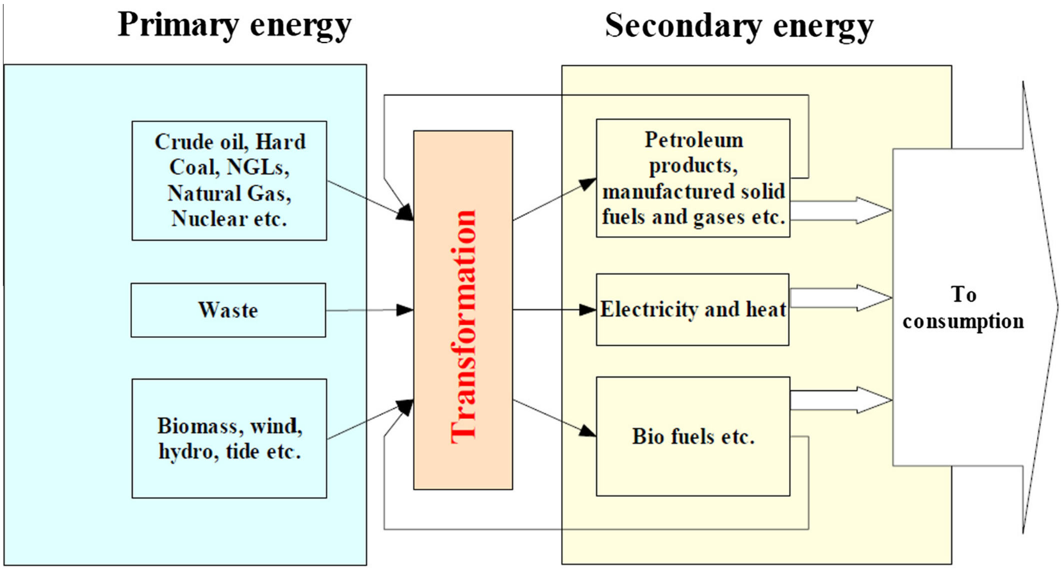


Fig. 1. Primary and secondary energy [1].

Table 1
Primary energy and conversion technologies.

Primary energy form	Conversion process	Secondary energy form
Crude oil	Oil refinery	Gasoline, diesel
Coal	Thermal power plant	Work, heat, electricity
Natural uranium	Nuclear power plant	Work, electricity, heat
Solar energy	Photovoltaic power plant	Electricity, heat
Solar energy	Solar thermal power plant	Electricity, heat, work
Wind energy	Wind farm (turbine)	Work, electricity
Falling or flowing water	Hydropower plant	Work, electricity
Tidal energy	Tidal power plant	Work, electricity
Biomass	Biorefinery, thermal power plant	Work, electricity, biofuel, biodiesel, heat
Geothermal energy	Geothermal power plant	Work, electricity, heat

form of heat which is usually lost to the environment. These waste heats are essential resources which if captured and stored, can serve as a useful energy resources for other processes. Apart from waste heat, energy storage will also play a significant role as the world moves to a low carbon economy where more energy is envisaged to be extracted from renewable resources. One major challenge facing most renewable energy resources, especially solar and wind, is that they occur intermittently which makes them unreliable for steady energy supply. Through the energy storage concept, these renewable resources can be made to be reliable and steady energy sources. This can be achieved by storing the excess energy generated when the renewable resources are available and re-use the stored energy when the renewable resources are not available.

1.2. The novelty of this review paper

Energy storage is a very wide and evolving subject area. Hence, it is necessary for us to emphasize on the area which this work focuses on. From the literature, most of the energy storage review papers focus on the technologies used for storing secondary energy forms. A good representation of the review papers in energy storage is as analysed below. Mahlia et al. [5] carried out a technical comparison of the different energy storage technologies with emphasis on their energy densities, economics and suitability for different applications, Chan et al. [6] reviewed the application of chemical heat pumps, thermodynamic cycles and thermal energy storage for low grade heat utilisation, Zhou et al. [7] reviewed the different energy storage technologies for marine current applications, Tan et al. [8] focused on the application of energy storage technologies for micro-grid processes, Kousksou et al. [9] investigated the different challenges faced by different energy storage technologies, Suberu et al. [10] analysed how energy storage can be used to mitigate the intermittency in renewable energy supply, Hassan et al. [11] reviewed the use of different energy storage technologies for wind energy system, and Chen et al. [12] looked at the progress in electrical energy storage using different technologies. The present work is different from most of the review articles already in the literature in the following ways. Apart from presenting an updated review of the different energy storage technologies for storing secondary energy forms, we have also covered the technologies used for storing energy in its primary form. The most distinguishing feature of our review paper to other reviews in this subject area is that we have carried out a detailed analysis of the different real life projects where most of the energy storage technologies have been applied as well as the future prospect of energy storage in the modern energy supply chain.

2. Energy storage (ES)

Literally, energy storage occurs in every facet of human society. The fundamental process of photosynthesis through which green plants generate food involves the conversion of solar energy from sunlight to chemical energy which is stored in plant cells. Storing fuel wood to provide heat during the winter or using it to maintain a fire is also a form of energy storage. Energy can also be stored as commodity or used to process materials which are storable. For example energy can be used to purify dirty water which can be stored as drinking water.

2.1. Scales of ES

In engineering term, energy storage is focused on the concept of storing energy in the form in which it will be reused to generate energy whenever needed. It is required for a wide range of different time and size scale as shown in Fig. 2. As indicated in the figure, the range of storage can be from capacitors which stores as little of 1 W h of energy for few seconds to chemical compounds which can be used for grid scale storage of several TW h of energy for years.

Generally speaking, primary energy serves to supply one of the three consumption sectors – transport, heat and electricity [13]. Energy storage has to meet completely different requirements for each of these consumption sectors, and the different storage concepts and technologies have to integrate in a concerted manner to provide the basis of an energy system.

2.2. Primary ES

The most common and stable form in which energy is stored is in its primary form. Most primary energy is usually obtained in storable forms. For example crude oil is stored in tank farms pending when they are sent to refineries for processing. Fig. 3a shows the world's largest crude oil tank farm located in Cushing, Oklahoma, USA. It holds about 62 million barrels of crude oil [14]. Natural gas as a form of primary energy can also be stored. It can either be stored in gaseous form in underground caverns or in tank farms in the form of liquid otherwise known as liquefied natural gas (LNG) (Fig. 3b) [15].

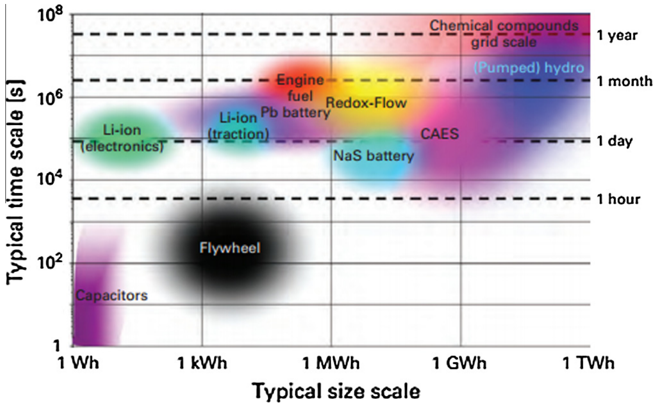


Fig. 2. Typical time and size scales associated with sufficient storage technologies [13].

Coal is also often stored in large piles prior to use, either in coal-fired power stations or industrial plants. Coal piles are designed in many shapes. Fig. 4 shows the different designs of coal storage domes [16,17]. Biomass is another form of primary energy which is storable. They can be stored as wood logs, wood chips, wood pellets which can be burnt when needed to provide energy. Fig. 5 shows the different forms in which biomass are stored.

The characteristics of primary energy storage forms are that they have very high energy density and can provide long term energy storage. However, since they only occur in natural form, they cannot be used as a medium for storing secondary forms of energy.

On the other hand, there are also some primary energy forms which are not storable. For example, most renewable energy resources are not easily storable in their natural form. Typical examples are wind, solar, tidal and wave energy. They can only be stored by converting them to secondary energy forms.

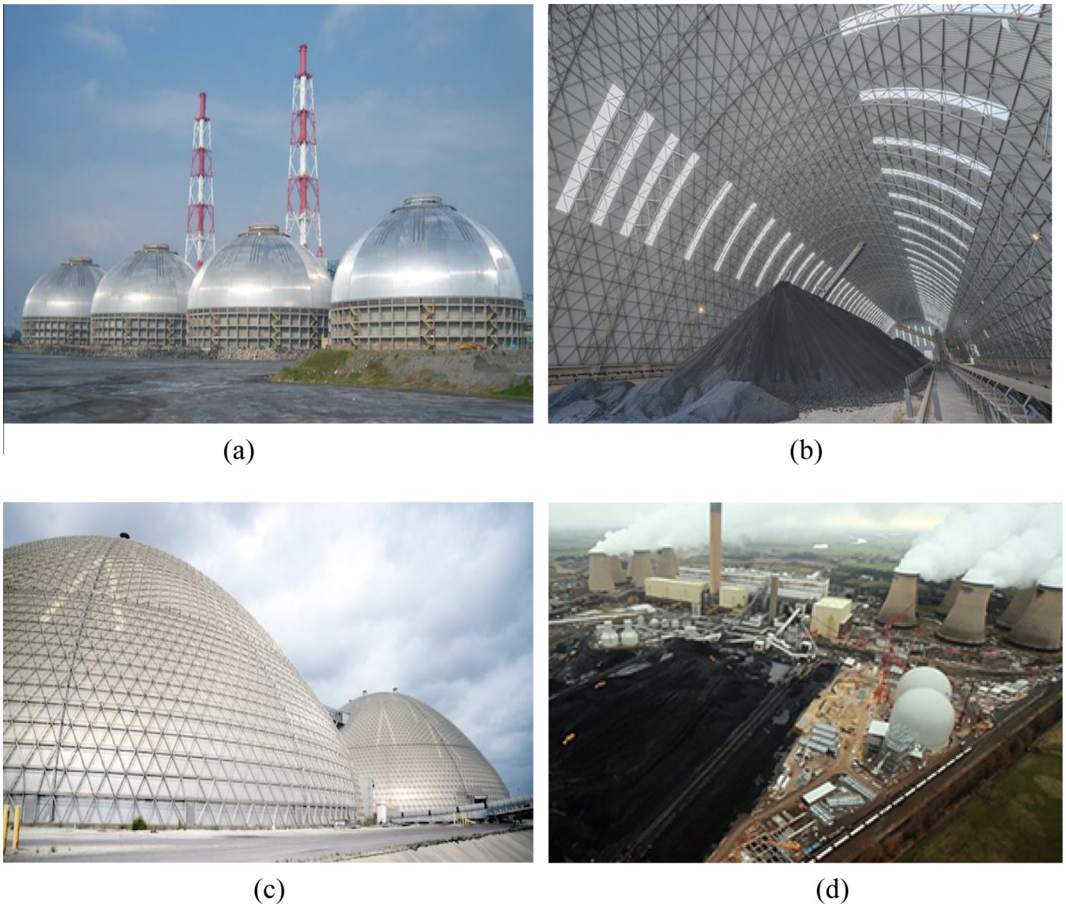
2.3. Secondary ES

Like the primary energy forms, some secondary energy forms especially those that are in the liquid and gaseous phase are easily storable. A good example is gasoline, diesel, biofuels (ethanol, butanol), hydrogen, methane and biodiesel. They are usually stored in tanks or high pressure containment vessels of various sizes and shapes.

The major challenge in the field of energy storage which is paramount in the field of engineering is in the storage of secondary forms of energy which neither occurs in the form of liquid nor gas. Some of these secondary energy forms include: work, heat, and electricity. From this point onward, the focus of this paper will be on the storage of secondary energy forms which occur in the form of heat and electricity as they are the most widely used form of secondary energy. The term energy storage (ES) will henceforth refer to this type of energy storage.

(a) (b)

Fig. 3. Crude oil and natural gas tank farm (a) in Cushing, Oklahoma, USA [14] and (b) in Brazoria County, Texas, USA [15].



(a) (b)

(c) (d)

Fig. 4. Coal storage domes (a) 180,000 t coal storage dome for power plants, Taiwan, (b) 60 m × 200 m longitudinal coal storage, Tunisia [16], (c) 122 m diameter storage dome with internal cladding, Florida, USA [16], and (d) coal pile feeding Drax Power Plant, England [17].

2.4. ES concept

The general concept behind secondary energy storage is to capture energy produced at one time for use at a later time. The process of capturing the energy is generally regarded as the charging while the process of releasing the energy to be used is regarded as the discharging. The energy is stored using different kinds of materials which are commonly referred to as the energy carriers. Fig. 6 shows the diagrammatically representation of the energy storage concept.

3. Benefits of energy storage

Energy storage has lots of benefits. It is important in energy management. It helps to reduce energy wastage and increase the energy utilisation efficiency [6,21] of process systems. Storage of secondary energy forms such as heat and electricity helps to reduce the quantity of primary energy forms (fossil fuels) consumed to generate them. This in turn not only lower CO_2 and other greenhouse gas emissions together with the associated global warming [5] but also help to conserve fossil fuels which are believed to be exhaustible. It can also play a crucial role in increasing the penetration of renewable, clean and intermittent energy resources such as wind energy, solar energy, and marine tidal current to the grid [7,22–24] as well as help in load shifting [9]. Energy storage helps in power system planning, operation and frequency regulation [8,12]. It helps to maintain energy systems stability, improve power quality in micro-grid systems as well as match demand with supply [8,24,25].

4. Energy storage technologies, their characteristics and real life applications

There are many technologies used for energy storage purposes. These technologies can be broadly classified according to the purpose for which the energy is stored. They include: electrical energy storage and thermal energy storage. Fig. 7 shows the different classes of energy storage technologies. From the figure, it can be seen that the technologies in which energy is stored in the form of thermal energy and released in the same form such as ice/chill water storage are classified as thermal energy storage technologies while those in which the energy is stored in the form of thermal but released as electrical energy such as liquid air energy storage are classified as electrical storage.

4.1. Electrical Energy Storage (EES) technologies and their characteristics

Electrical energy is regarded as one of the most readily available form of energy. It is a common consumer good [25] and ranked only second to oil in consumption in 2012 [2]. Presently, the production of electricity is highly centralized with power plants located far from the end users. Grid load levelling is usually based on the prediction of daily and seasonal usage using historical trends. When production is not sufficient, peaking power plants such as gas turbine and hydroelectric systems are usually deployed to meet the shortfall. The increased decentralization of power generation combined with the high penetration of renewable intermittent power generation such as wind, solar and tidal into the grid

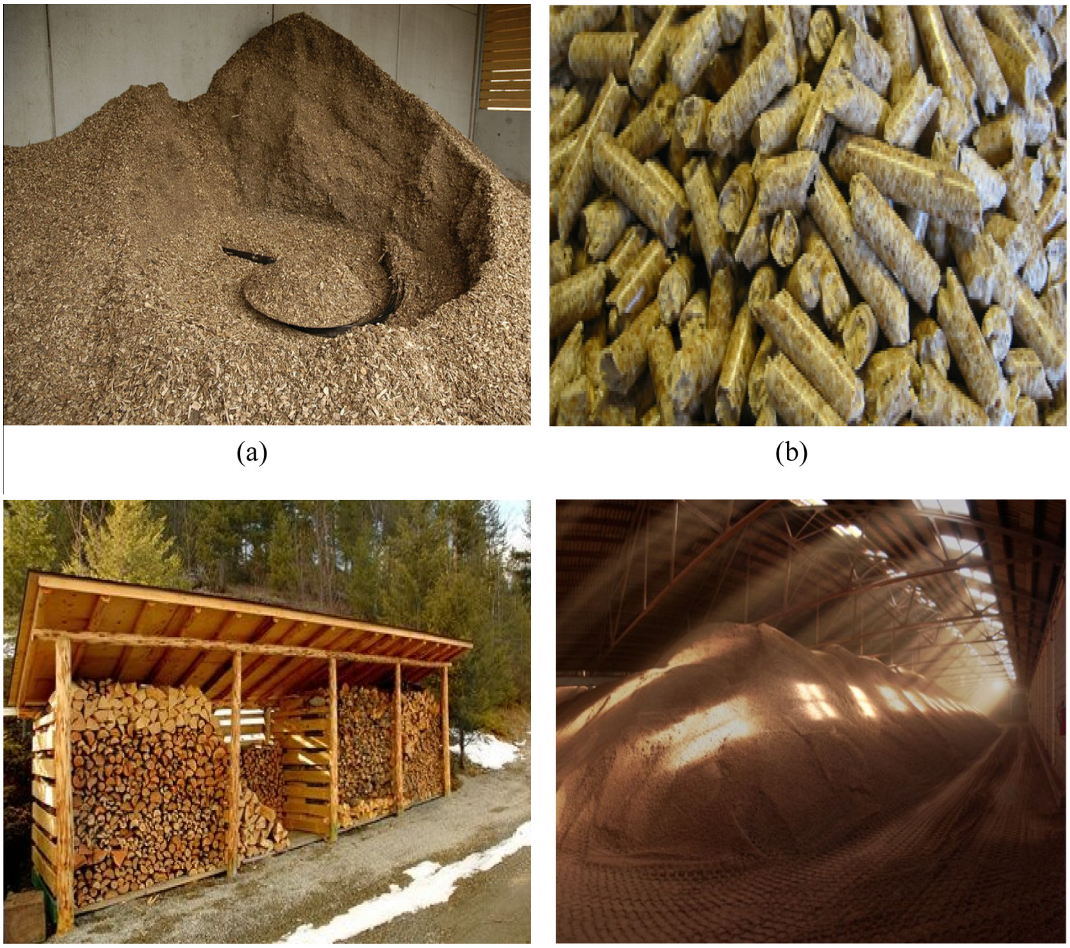

(a) (b)
(c) (d)

Fig. 5. Forms of biomass storage (a) wood chips [18], (b) wood pellets [19], (c) wood logs, and (d) wood dust [18].

Fig. 6. Energy storage concept [20].

systems has resulted in increased difficulty of stabilizing the power network, mainly due to the imbalance in supply and demand [10,25,27–29]. Due to the aforementioned factors, the storage of electrical energy has become a necessity. Electricity in its form is not storable. The only way through which it can be stored is by converting it into a more stable energy form which is storable with the intent of transforming it back to electricity when needed. There are various technologies which can be used to convert electricity to other forms of energy which can easily be stored. These technologies are regarded as electrical energy storage technologies and can be grouped as follows: mechanical energy storage, chemical energy storage, electrochemical (supercapacitor energy storage, battery energy storage), superconducting magnetic energy storage and thermal energy storage.

4.1.1. Mechanical Energy Storage (MES)

These are electromechanical systems which convert electrical energy into forms of energy which are easily storable. Examples of mechanical based energy storage systems include: flywheels, pumped hydro energy storage, gravity power module, compressed air energy storage, liquid-piston energy storage.

4.1.1.1. Flywheel Energy Storage (FES). Flywheel energy accumulators comprises of composite flywheel coupled with motor generator and brackets (often magnetic), with a low pressure casing which helps to reduce self-discharge losses [25,30]. Its principle has been in use since the 1950s when it was used to build “gyro buses” [5]. As an energy storage device, flywheel was designed to deal with short voltage disturbance in order to improve power quality [11,12,27]. It stores electrical energy in the form of rotational kinetic energy [8]. Fig. 8 shows the diagram of a flywheel system with its parts [31]. As an energy storage device, flywheel operates in the charging and discharging mode.

During the energy storage mode otherwise known as the charging phase, the electrical energy is used to accelerate the motor which is connected to the rotor (the rotating mass) via a shaft.

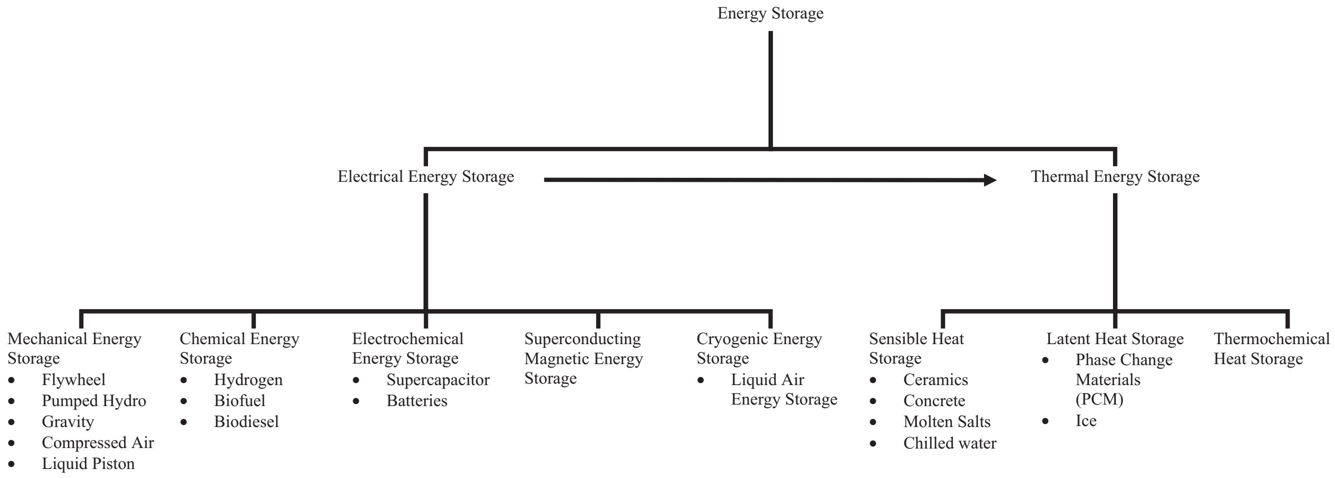


Fig. 7. Energy storage technologies classification [26].

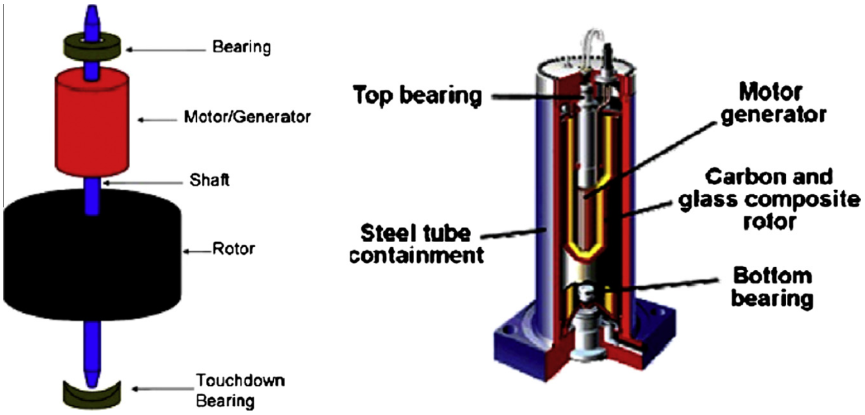


Fig. 8. Flywheel [31].

The rotation of the shaft transfers an angular momentum to the rotor which acts as the energy storage component. During the discharging phase, the rotating mass transfers the kinetic energy as it decelerates back to electrical energy using the generator connected to the same shaft. The motor/generator unit of the device is the same. During the charging phase, the device acts as a motor while during the discharging phase it acts as the generator. Flywheels are broadly classified into two classes based on the rotational speed. Low speed flywheels are those with rotational speed of less than 10,000 rpm while high speed flywheels have rotational speed greater than 10,000 rpm [7]. Low speed flywheels provide a shorter period of storage with high power capacities while high speed flywheels are the opposite [5]. In terms of cost of operation and operability, flywheels are regarded as perfect model of energy storage device due to its low maintenance cost, long life cycle, high efficiency, free from depth of discharge effects, environmentally friendly, wide operating temperature range and ability to survive in harsh conditions [5,7]. However, as a result of friction losses, flywheels are not good for long term energy storage. The presence of frictional forces lowers the efficiency of the flywheel device during operation. For example a flywheel can attain an instantaneous efficiency of 85% after charging. This can drop to about 78% after 5 h and 45% after one day [25].

4.1.1.2. Pumped Hydroelectric Energy Storage (PHES). PHES is the most mature and widely used large scale energy storage technology. It uses gravity to store energy. It stores electrical energy by pumping water uphill using off-peak electricity. The water is stored in reservoirs otherwise known as the upper reservoir and only released downhill to the lower reservoir to drive a generator in order to produce electricity when it is needed. According to the 2010 survey carried out by the Electric Power Research Institute (EPRI), PHES makes up more than 99% of the global large scale energy storage installation [32]. They are capable of providing reliable power within a short period of time (typically within 1 min) [31]. Their efficiency is in the range of 65–85% [5,10,25,31], with some installations claimed to have achieved an efficiency of 87% [33]. PHES was firstly constructed in Italy and Switzerland in 1890 and later in the USA at the beginning of 1929 [5]. PHES system can be incorporated into natural lakes, rivers, or reservoirs. This technology is known as open-loop pumped hydro energy storage or it can be constructed independent of existing natural water sources as a closed-loop system [34]. Presently, there are over 150 plants with 22,000 MWe capacity in the USA and 78,000 MWe of installed capacity worldwide [33]. One limitation of PHES is that several natural geological features are needed, including adequate close land areas divided by adequate elevation. There must also be an adequate supply of water. Fig. 9 shows the diagram of a PHES.

4.1.1.3. Gravity Energy Storage (GES). Because of the geological limitations and water requirement encountered with PHES, there have been many adaptations to the pumped hydro concept. These adaptations are geared towards eliminating the aforementioned limitations. Like pumped hydro concept, these technologies depend on

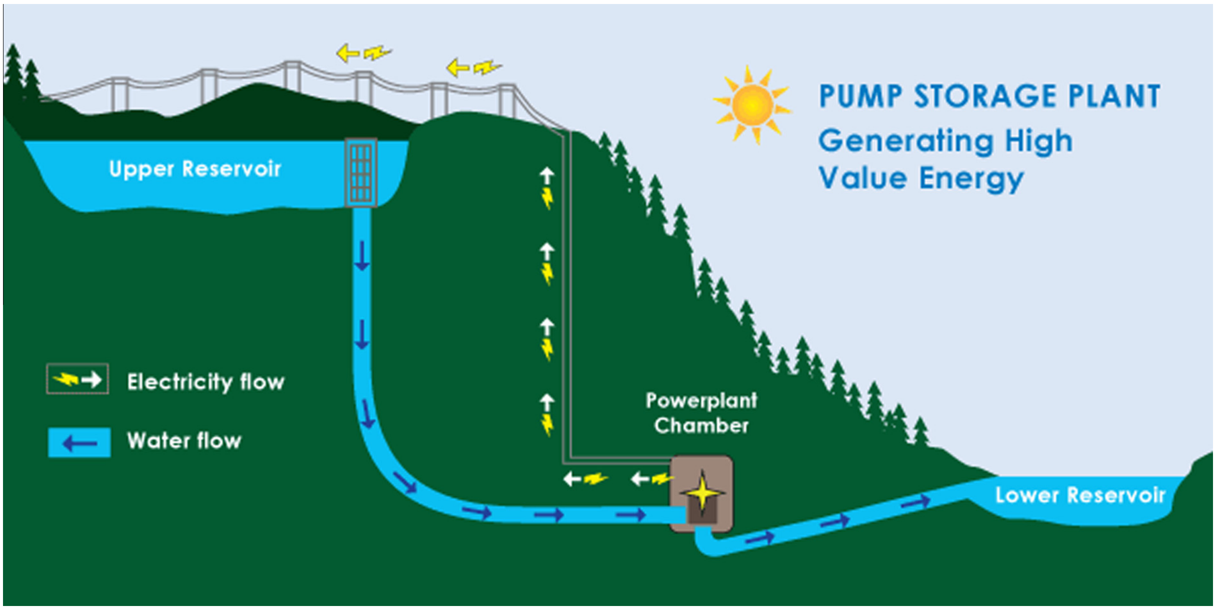


Fig. 9. Pumped hydroelectric energy storage.

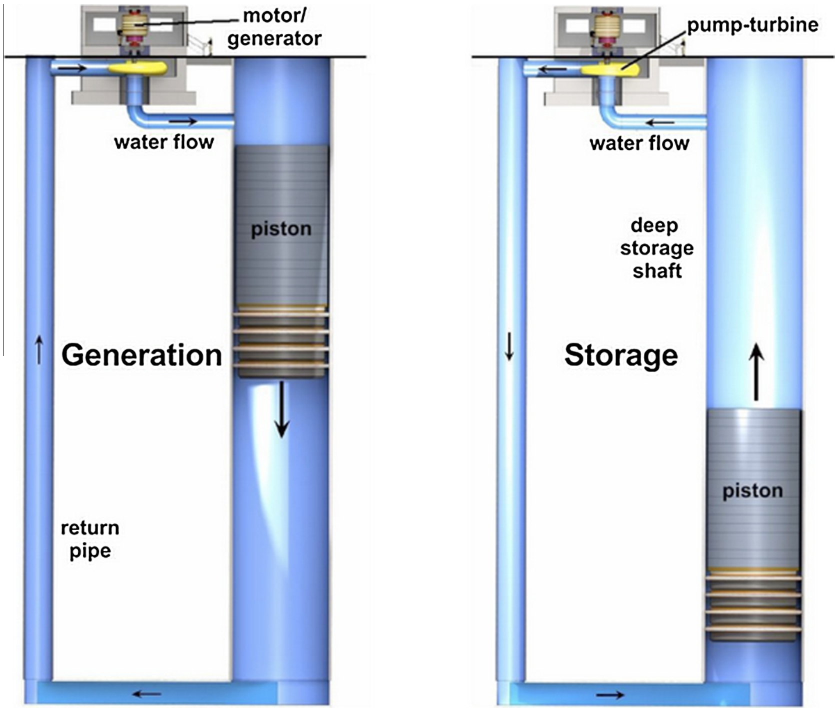


Fig. 10. Gravity Power Module (GPM) [35].

gravity and are generally called Gravity Energy Storage (GES) technologies. An example of such technology is the Gravity Power Module (GPM) technology developed by Gravity Power [35]. As shown in Fig. 10, this technology uses a very large piston that is suspended in a deep water filled shaft with sliding seals which helps to prevent leakage around the piston.

The system operates as a closed loop which means that the shaft is only filled with water once, mainly at the start of the operation. During the charging mode, the off peak electricity is used to drive the motor/generator which spins the pump to force water down the return pipe and into the shaft thus lifting the piston. The piston is held at the high position until when power is needed during the discharging mode. In the discharging mode, the piston drops forcing water down the storage shaft up the return pipe and through the turbine which spins a motor/generator to produce electricity. Although there is currently no GPM installation, the developers claim that it can achieve an efficiency more than 80% [35].

A new GES solution developed by Energy Cache uses electricity during off peak period to move buckets of gravel to high elevation (Fig. 11). These buckets are released during peak period to release the energy.

Another technology which is based on the same concept uses boxcars (train-like system) as shown in Fig. 12. The system operates by using off-peak electricity during the charging phase to move concrete blocks up an elevation such as on top of mountains. The blocks are then allowed to descend under gravity during peak period to generate electricity during the discharge phase. This technology is being pioneered by a company called Advanced Rail Energy Storage. They both claim that their systems can achieve an efficiency of about 90%. However, they still suffer the same topological constraint as pumped hydro [37].

Fig. 11. Energy Cache 50 kW Gravity Energy Storage (ECGES) demonstration plant in California [36].

Fig. 12. Advanced Rail Energy Storage (ARES) demonstration plant [37].

4.1.1.4. Compressed Air Energy Storage (CAES). CAES system uses off peak electricity to compress air and store it in a reservoir either an underground cavern or aboveground pipes or vessels [38]. This air is released during peak period, heated, expanded and used in a turbine-generator to produce electricity. The process diagram of a CAES is shown in Fig. 13. It is second to PHES in terms of commercial bulk energy storage plant available today. The technology was first introduced in 1970s as a load following and peaking power system [5]. For a given amount of fuel, it is capable of producing three times the electricity produced from a conventional gas turbine system since no air compression is required. Underground hard rock caverns, salt caverns, depleted gas fields or an aquifer are usually used as the reservoir. Over-ground high pressure containment can as well be used as reservoirs [38]. CAES has an estimated efficiency of 70% with an expected lifetime of about 40 years [9]. Several options have been explored on how to make CAES more attractive. They include: to reuse the compression heat during the expansion process in order to either eliminate or reduce the quantity of natural gas consumed during the power generation (i.e. discharging) phase and Compressed Air Storage with Humidification. There are two commercial plants using CAES for energy storage application. They include: a 290 MWe Huntorf air storage gas turbine power plant in Germany and a 110 MWe CAES in McIntosh, USA [12]. There are also some plants being planned or under construction [12].

4.1.1.5. Liquid-Piston Energy Storage (LPES). This is relatively a new energy storage concept which is yet to be commercialised [40]. It is believed that this technology can be used to substitute lead-acid batteries in certain standalone stationary applications. It provides a near isothermal behaviour [40,41] due to the low speed of the compression/expansion process which is distributed over all the

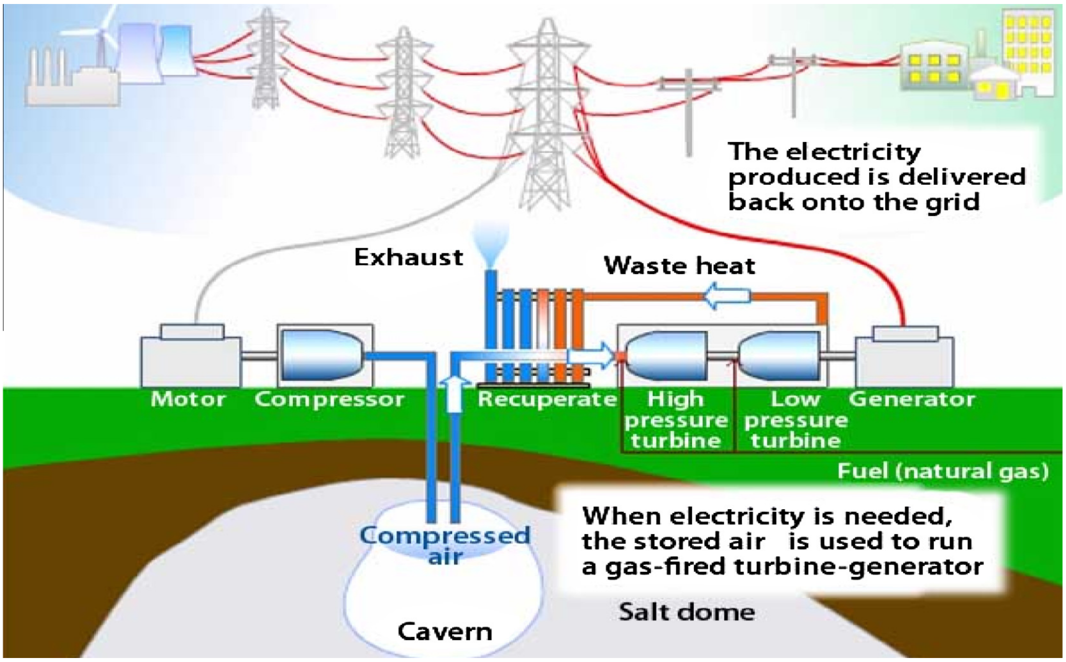


Fig. 13. Process diagram of CAES [39].

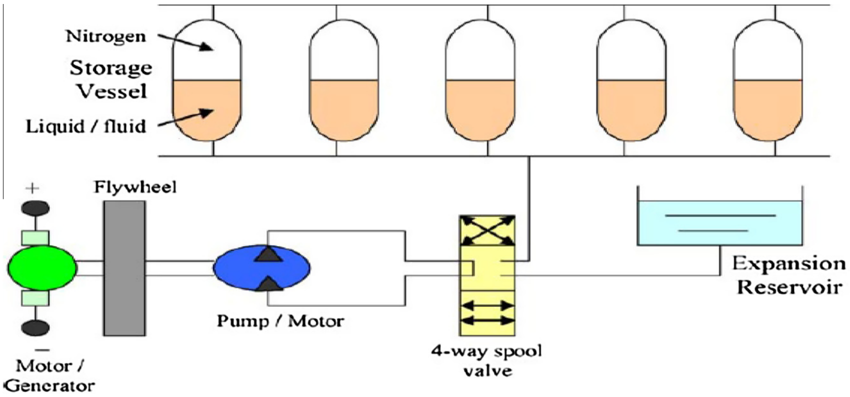


Fig. 14. Liquid-piston energy storage [40].

storage vessels. The schematic diagram of the process is shown in Fig. 14.

It operates by modulating the compression and expansion of a trapped volume of gas – usually nitrogen in a vessel using a liquid. The gas pressure varies from 100 bar (with no liquid) to 250 bar (with 50% of vessel filled with liquid). As an energy storage device, during the charging phase, electricity is passed to the high efficiency fixed displacement pump/motor which pumps the liquid into the vessel thus compressing the gas contained there. The energy is stored in the compressed gas until when energy is needed. During the discharge phase, the compressed gas is expanded and the fluid is expelled from the vessels to the pump/-motor which drives the generator to provide electricity. The system is usually provided with a solenoid powered 4-way spool valve which works in conjunction with a flywheel designed to maintain a low-rippled speed for the motor/generator as well as a liquid reservoir which helps store liquid. Compared to lead-acid batteries, this technology has the following advantages: unlimited cycling ability, lower maintenance, storage capacity unaffected by age, undamaged performance in cases of full discharge, impossible overcharge due to the presence of relief valves, power supply is unlinked to capacity, almost zero self-discharging [40]. However, it has lower energy density (from 3.2 to 5.55 W h/kg) and there are chances of leakage at the piping assembly, it also has lower energy efficiency, at around 73%, compared to a new lead-acid battery. Although the energy density can be increased by increasing the pressure, there is always a limitation to the maximum pressure that is allowed by the hydraulic system components.

4.1.2. Chemical Energy Storage (CES)

Chemical energy storage envelopes all technologies where the electrical energy is used to produce chemical compounds which can be stored and used when needed for energy generation. Most chemical compounds which are used as energy storage media has higher energy density than pumped hydro and CAES and this makes them an ideal energy storage medium. There are several chemical compounds which are currently been considered for energy storage application. They include: hydrogen, methane, hydrocarbons, methanol, butanol and ethanol. Butanol and ethanol are mainly produced through fermentation of biomass and thus are not considered as electrical energy storage technique. Amongst the remaining listed compounds, hydrogen is regarded as the shortest route to chemical compound from electricity. Hydrogen is produced through the electrolysis of water and all other compounds (i.e. methane, hydrocarbons and methanol) can be produced from hydrogen in the presence of a carbon source such as CO and CO_2 using the Fischer-Tropsch synthesis [13]. For electricity generated through fossil fuels, it is worthless to store the electricity by hydrogenating CO_2 to produce liquid hydrocarbon or methanol as this can lead to too much losses. Hence, the conversion of the hydrogen directly to electricity should be the most promising technology. Based on the argument, only the storage of electricity in form of hydrogen is considered in this paper.

4.1.2.1. Hydrogen Energy Storage (HES). Hydrogen energy storage is one of the most popular chemical energy storage [5]. Hydrogen is storable, transportable, highly versatile, efficient, and clean energy carrier [42]. It also has a high energy density. As shown in Fig. 15, for energy storage application, off peak electricity is used to electrolyse water to produce hydrogen. The hydrogen can be stored either as compressed gas, liquefied gas, metal hydrides or carbon nanostructures [43]. The choice of the storage technology depends on the characteristics of available technologies in terms of technical, economical or environmental performance [44]. During the discharge phase, the stored hydrogen is either used in fuel cell or burnt directly to produce electricity. One major drawback in using hydrogen for electricity storage is the substantial energy losses during a single cycle [13]. For example, electrolysis currently have an efficiency of 60%, transport and compression for storage may lead to another 10% efficiency loss (although this can be lower) while reconversion to electricity has a efficiency of about 50% for fuel cell application (higher efficiency is anticipated for combustion based power generation if cogeneration of heat is integrated). Thus, the overall round trip efficiency may be in the neighbourhood of 30%. This is partially compensated by the high storage density.

4.1.3. Electrochemical energy storage

4.1.3.1. Supercapacitor energy storage. Supercapacitors (SCs) also known as electrochemical capacitors (ECs), ultra-capacitors or electric double layer capacitors [42,45] were attracting less attention until very recently [46] when faster energy storage systems were needed in a number of applications to replace Li-ion batteries which suffer from sluggish charge/discharge with a limited lifetime. This renewed interest has resulted in great progress in its development and use in energy storage technologies. For example, the common arrangement of solid dielectric between the electrodes in conventional capacitors is now replaced with the use of an electrolyte solution placed between two solid conductors as is the case with SCs [30]. This gives the SC a much larger capacitance, energy density and compactness compared with the conventional capacitors [12,47–49]. SCs stores energy in the two series capacitors of the electric double layer which is formed between each of the electrodes and the electrolyte ions [8]. They are capable of storing large energy density and can respond to any change in power demand in tens to hundreds of milliseconds [8,31]. The most

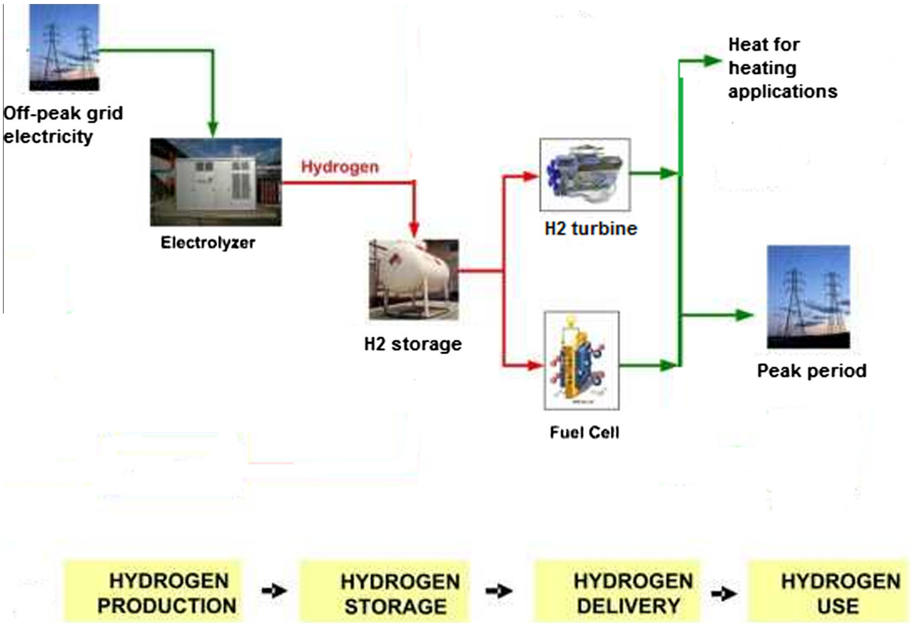


Fig. 15. Hydrogen energy storage process.

important challenge facing SC is the need to reduce its cost and increase its energy density to ⩾10 W h/kg thus moving them closer to batteries [45,50]. One way of achieving this is by increasing the capacitance and/or the cell voltage. The number of charge and discharge cycles of SCs is nearly unlimited but the energy throughput in fast cyclic operation is limited [9]. They have an efficiency of 95% and 5% per day self-discharge, meaning that the stored energy must be used quickly [25]. Fig. 16 shows the schematic diagram of capacitor storage system.

4.1.3.2. Battery energy storage. Secondary or rechargeable battery is regarded as the oldest electrical energy storage device [51,52] which stores electricity as chemical energy. It is an electrochemical device with the ability to deliver energy, in the form of electrical energy, using the chemical energy generated by electrochemical reactions [53]. Batteries are built in different sizes with capacity ranging from less than 100 W to several megawatts. Their round trip energy storage efficiency is in the range of 60–80% depending on the operational cycle and the electrochemistry type [8]. Battery system technology is the most widespread energy storage device for power system application [54–56]. Apart from the electric grid, their energy storage application covers sectors such as hybrid electric vehicles (HEV), marine and submarine missions, aerospace operation, portable electronic systems and wireless network systems. Batteries come in different varieties depending on their application. Deep cycle type batteries are the most commonly used for power system application and they have efficiency range of 70–80% [54,57]. There are different types of batteries used in energy storage application and they include: sodium sulphur battery, sodium nickel chloride battery, vanadium redox battery, iron chromium battery, zinc bromine battery, zinc air battery, lead acid battery, lithium ion battery, nickel cadmium battery, etc.

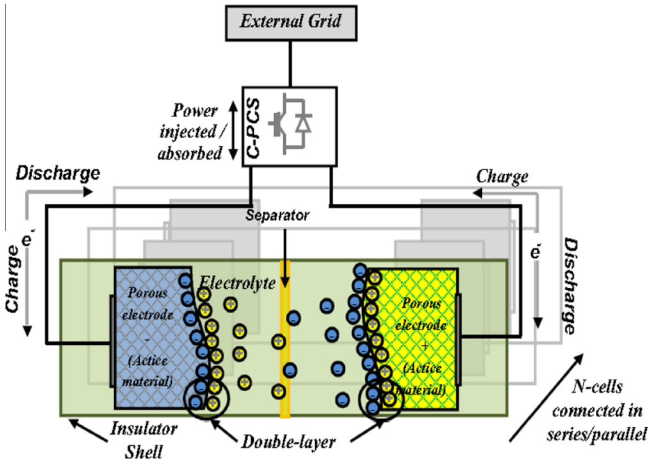


Fig. 16. The capacitor storage system [9].

4.1.3.2.1. Sodium Sulphur (NaS) battery. NaS is one of the batteries used for commercial electrical energy storage in electric utility distribution grid support, wind power integration and high-value grid services [38]. Its potential comes from its ability to provide high energy density (151–170 kW h/m^3), better energy efficiency (>85%), long cycle capability (2500 cycles upon 90% depth of discharge) enhanced energy storage capacity and long discharge period (approximately 6 h) [10,38,58–60]. Its capability to provide prompt and precise response makes it useful for applications in grid power quality regulation. As shown in Fig. 17, NaS battery is made of liquid (molten) sulphur at the positive electrode and liquid (molten) sodium at the negative electrode.

The electrodes are separated with a solid beta alumina ceramic electrolyte [59]. It is economical with low maintenance cost. The reason is because the material of construction is affordable and also recyclable. They operate in the temperature range of 300–350 °C during the discharge and charging cycles. During the discharge phase, the sodium (negative electrode) is oxidized at the sodium/beta alumina interface, forming Na$^+$. These ions move through the electrolyte and combine with sulphur that is being reduced at the positive electrode to form sodium pentasulphide (Na_2S_5) which is immiscible with the remaining sulphur thus leading to a two-phase liquid mixture (see Fig. 18). After consuming all the free sulphur available, the Na_2S_5 becomes progressively converted to single phase sodium polysulphides (Na_2S_{5-x}) with increasing sulphur content. The disadvantages of NaS battery are high capital cost, high operational temperature requirement and high operational hazard due to the use of metallic sodium which is combustible if exposed to water.

4.1.3.2.2. Sodium Nickel Chloride ($NaNiCl_2$) battery. Like NaS, NaNiCl batteries are high temperature devices. They operate at normal temperature range of 270–350 °C [38] and were primarily developed for application in electric vehicles (EV) and hybrid electric vehicles (HEV) [58,61]. During the charging phase, NaCl salt and Ni are transformed into $NiCl_2$ and molten Na. This chemical reaction is reversed during the discharging phase (see Eq. (1)). One advantage of the process is that no side reaction occurs.

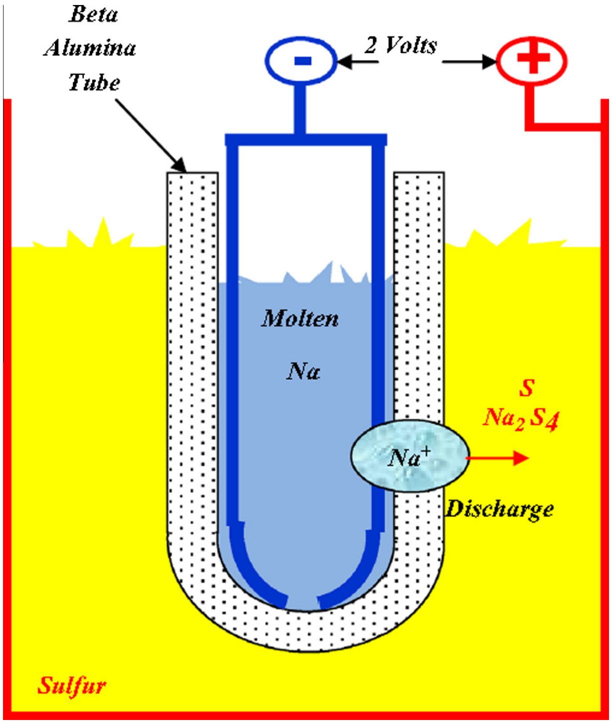


Fig. 17. NaS battery [9].

$$2NaCl + Ni \rightleftarrows NiCl_2 + 2Na \tag{1}$$

The battery uses a wall material made of ceramic as the electrolyte. This electrolyte helps to separate the electrodes from each other. The electrolyte conducts only Na^+ but isolates electrons. This means that the reaction can only proceed when there is an external circuit which allows the flow of electron of equal amount as the Na^+. The porous solid $NiCl_2$ cathode is impregnated with a Na^+ conductive salt ($NaAlCl_4$) that provides a conductive path between the inside wall of the separator and the reaction zone [38] (see Fig. 19).

4.1.3.2.3. Flow battery - Vanadium Redox Battery (VRB). Vanadium reduction and oxidation (redox) battery (VRB) belongs to a group of batteries known as flow batteries. This is the type of battery in which one or both active material is in the electrolyte solution at all times [38]. The operation of VRB is based on the redox reaction of different ionic forms of vanadium (see Fig. 20). As a flow battery, its advantage over the conventional battery types is that it is possible to design the system with optimal power acceptance and delivery properties without needing to maximize the energy density [5]. This is possible due to the separation between the power and energy requirement. Furthermore, it can achieve stable and durable performance since the electrodes do not undergo physical and chemical changes during operation. For the case of VRB, the V^{3+} is converted to V^{2+} ions at the negative electrode during the charging operation. At the same time at the positive electrode, V^{4+} ions are converted to V^{5+} ions through the release of electrons. These reactions absorb the electrical energy and convert it to chemical energy. During the discharge phase, the reactions are reversed which leads to the release of the stored chemical energy to electrical energy. VRB can achieve an efficiency of about 85% [5]. Their advantages include: low maintenance cost, tolerance to overcharging, and ability to be deep charged without affecting the cycle life. On the other hand, the need for pumps, sensors, power management and secondary containment makes them unsuitable for small scale energy storage application [63].

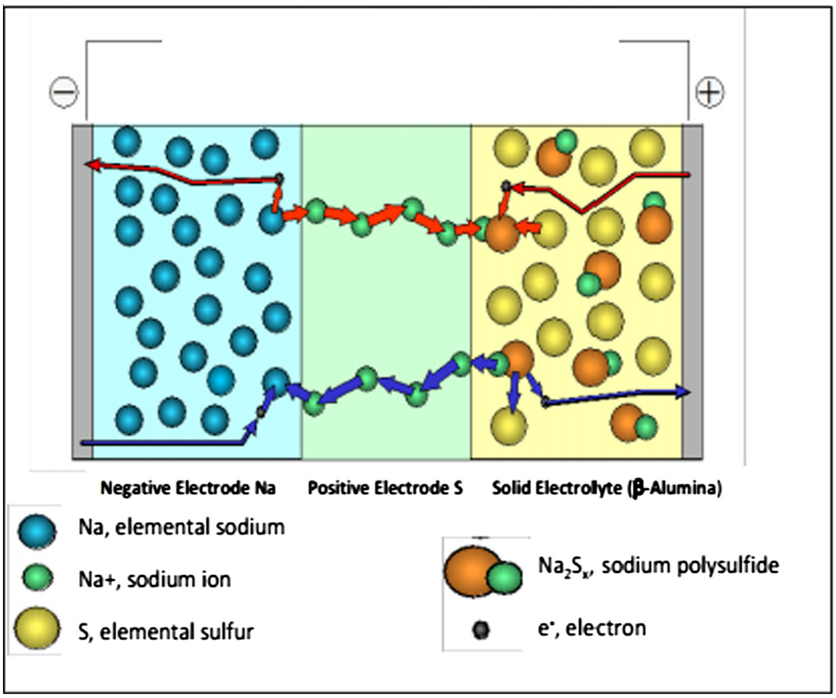


Fig. 18. NaS operation [38].

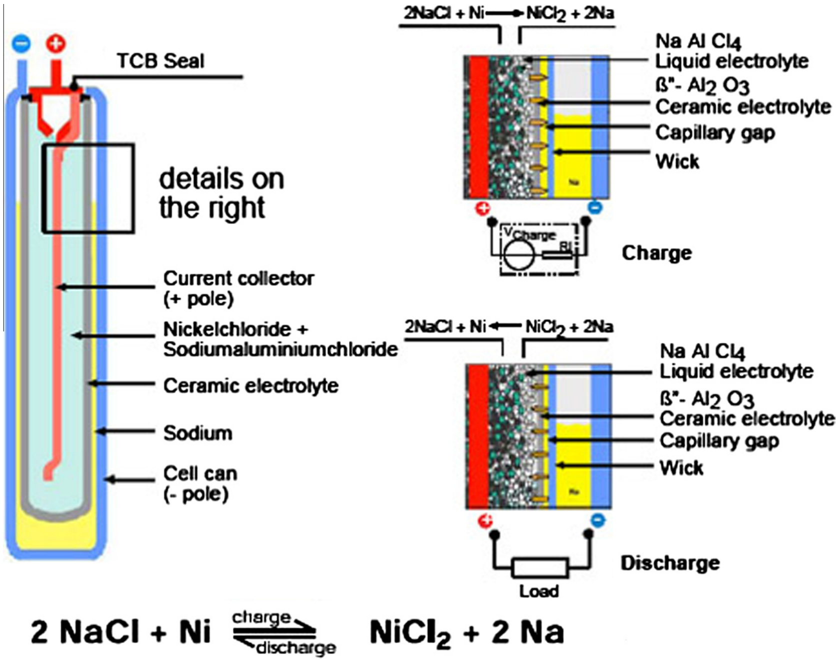


Fig. 19. Sodium nickel chloride battery [62].

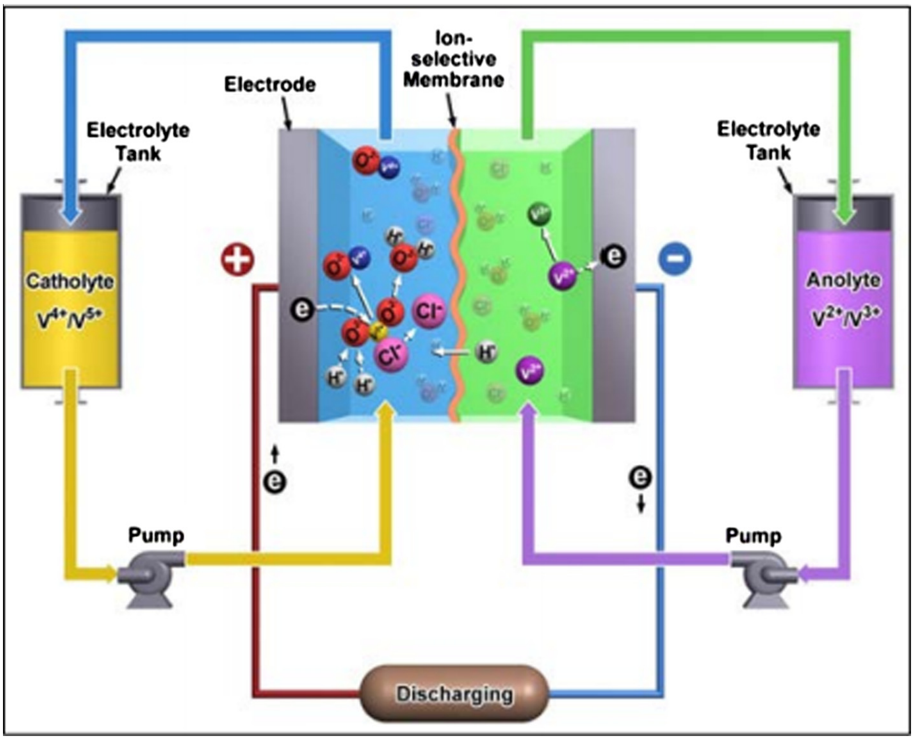


Fig. 20. Principles of the vanadium redox battery [38].

4.1.3.2.4. Flow battery - Iron Chromium (FeCr) battery. This is another type of flow battery but unlike the VRB, the FeCr battery is still in the R&D stage. Their low cost structure makes them attractive for grid storage solutions however, because it is still mainly in the R&D stage [38], there is still high uncertainties in its performance and cycle life. It uses liquid reactants in which only a small volume is electrically active and the cells are hydraulically balanced. The volume of the reactant remains constant during cycling. Fig. 21 illustrates the principle of operation of the FeCr battery.

It can find application in grid time shifting on either the utility or customer side of the meter and also for frequency regulation services.

4.1.3.2.5. Flow Battery - Zinc bromine (ZnBr) battery. This also belongs to the family of flow batteries [10,25]. It comprises of two electrode surfaces and two electrolyte flow stream separated

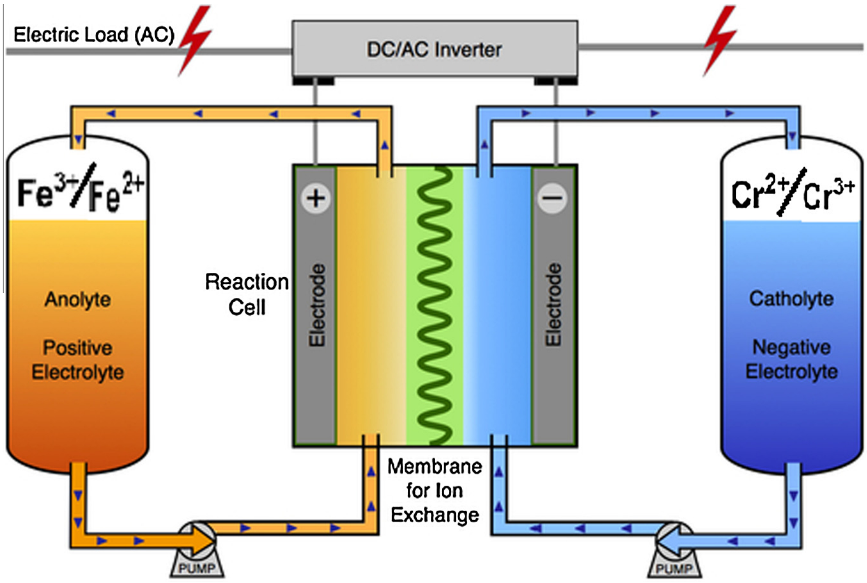


Fig. 21. Principle of FeCr battery [64].

by a micro-porous film [38]. The electrolytes are aqueous solutions of zinc bromine. The positive electrolyte is called the catholyte while the negative is the anolyte. During the charging operation, off peak electricity is introduced into the system which results in the deposition of zinc onto the negative electrode while bromine is form at the positive electrode. The zinc and bromine ions migrate to the opposite electrolyte via the micro-porous separator in order to achieve charge equalization. The electrodes are composed of bipolar carbon plastic due to the corrosive nature of bromine. Fig. 22 shows the schematic diagram of ZnBr battery.

4.1.3.2.6. Zinc Air (ZnAir) battery. This is an example of metal air battery. Metal air batteries make use of an electropositive metal in an electrochemical couple with oxygen from the air to generate electricity. Apart from zinc, examples of metals that can be used in the battery include: aluminium, magnesium or lithium. They are the most compact and potentially the least expensive batteries available [31]. However, they have low efficiency (50%) and can only achieve a few hundred cycles. Fig. 23 shows the principle of operation of zinc-air battery.

The battery produces electricity when the air electrode is discharged with the help of catalysts that produce hydroxyl ions in the liquid electrolyte. This process is reversed when the battery is recharged and oxygen is released into the air electrode. The major challenge with the development of this battery is avoidance of CO_2 impacts from the air on the electrolyte and cathode as well as avoiding Zn dendrite formation.

4.1.3.2.7. Lead Acid (PbO_2) battery. This is the oldest rechargeable battery for both household and commercial application. Its use for commercial application is limited due to the development of other high efficient and high energy density batteries. PbO_2 is still

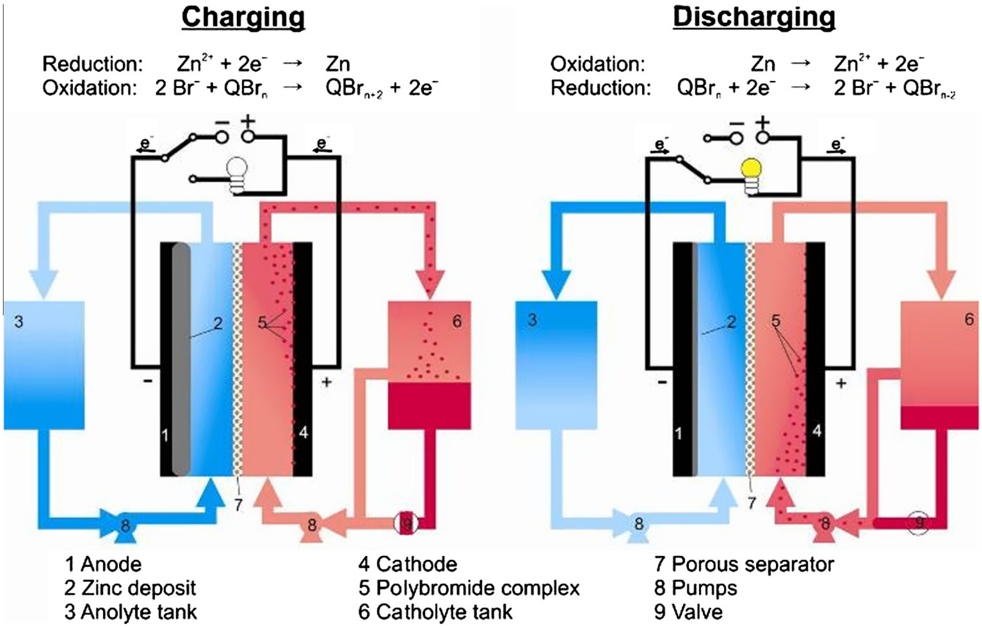


Fig. 22. ZnBr cell configuration [38].

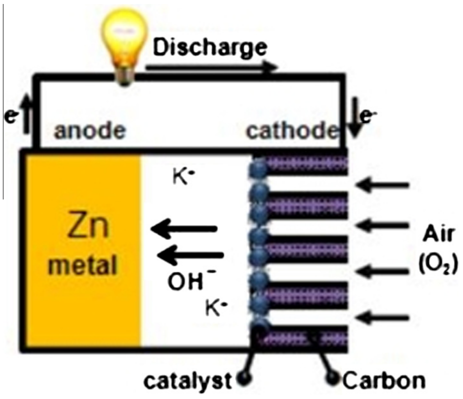


Fig. 23. Zn-air battery operation [31].

being used predominantly in some applications because of its low cost, reliability, maturity level in technology, extended life span and fast response especially in automobile systems [10]. It is composed of a positive electrode made of lead-dioxide and a negative electrode made of metallic lead with an electrolyte made of tetraoxosulphate (VI) acid. It has a rated voltage of 2 V, energy density of about 30 W h/kg and power density of around 150 W/kg [40]. Its energy efficiency ranges from 85% to 90% with low maintenance and investment cost. The self discharge rate is also very low. Other variants of the traditional lead-acid battery include the carbon lead-acid and advanced lead acid. The former involves the incorporation of carbon in one or both electrodes while the later involves the following: carbon-doped cathodes, granular silica electrolyte retentions, high density positive active material and silica based electrolyte. Fig. 24 shows an illustration of the PbO_2 battery.

4.1.3.2.8. Lithium ion (Li-ion) battery. These batteries uses lithium metal or lithium compound as anode [5]. This type of battery is used for mainly portable electronics and medical devices [30]. The Li-ion batteries are lighter, smaller and more powerful than other batteries which make it attractive for consumer electronics [5]. Their energy and power density range from 90 to 190 W h/kg and 500 to 2000 W/kg [40,54]. They also have high efficiency and low self-discharge rate making it suitable for EV solutions [65]. The new advanced Li batteries developed using nanowires silicon are capable of producing 10 times more electricity than the existing Li-ion batteries [5].

There major drawback is that they are fragile with temperature dependent life cycle. They usually require a special protection circuit to avoid overload. These together with the high capital cost ($900–1300/kW h) limit their use for large capacity applications.

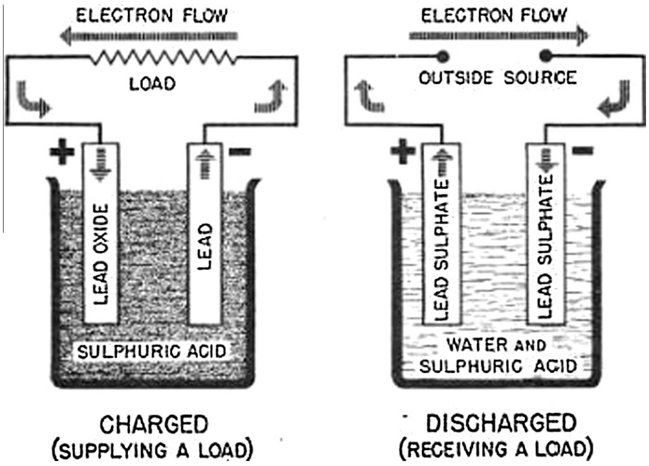


Fig. 24. Lead-acid battery [66].

4.1.3.2.9. Nickel Cadmium (NiCd) battery. This is one of the most developed nickel based batteries. It uses nickel oxy-hydroxide and metallic cadmium as the electrodes. It was the dominant rechargeable battery in the 90s. They are characterised by fast recharge, long cycle life, deep discharge rates with no damage or loss of capacity [30,67]. They can achieve about 3000 cycles [54]. However, their application is limited by cost (they cost 10 times more than the lead-acid) and the cadmium toxicity poses environmental concern [40,54,65,68].

4.1.4. Superconducting Magnetic Energy Storage (SMES)

SMES uses magnetic field to store energy which has been cryogenically cooled to a temperature below its superconducting critical temperature [5,69]. It occurs by inducing DC current into coil made of superconducting cables of nearly zero resistance (usually made of niobiumtitane (NbTi)) filaments that operate at very low temperature of about −270 °C [69,70]. SMES consists of three parts namely superconducting coil/magnet, power conditioning system and cryogenically cooled refrigeration [71]. The DC current increases during charging while the reverse is the case during the discharging operation. Although the system requires considerable quantity of energy to attain cryogenic condition and the current has to flow through non-superconducting material and solid state switches which cause resistive losses, the overall efficiency in commercial applications in the range of MW is very high [69]. The superconducting coil is made of either solenoid or toroid. Solenoid is simpler and easier to control while toroid offers low stray field which is an advantage in SMES applications [72]. They are capable of providing rapid response for either charge or discharge with a response time of a few milliseconds [12]. They also have a very high lifetime but its major drawback is the cost (both capital and operating).

4.1.5. Cryogenic energy storage

4.1.5.1. Liquid Air Energy Storage (LAES). As the name implies, LAES involves the storage of electrical energy in the form of liquid air. It is also known as cryogenic energy storage (CES). This technology is currently being pioneered by Highview Power Storage, UK [73] with a demonstration plant in Slough, UK. The first stage of the process is similar to the compression stage of the CAES. The compressed air is then liquefied and stored in a tank at a pressure close to atmospheric pressure. During the power generation (i.e. discharging) phase, the liquid air can be pumped and used to provide direct cooling, refrigeration, and air conditioning before being vaporised using waste heat followed by expansion to generated electricity. One main advantage of this process is that liquid air occupies 1/700th of volume occupied by gaseous air which results in the storage of large quantity of air in small containment. However, it has a relatively low efficiency (40–70%) [74,75]. As this technology is currently in the demonstration stage, there is still room for efficiency improvement especially by improving the liquefaction process and using the compression heat during the power generation stage. Fig. 25 shows the schematic of the LAES process.

4.2. Electrical energy storage technologies and real life applications

4.2.1. Intermittent balancing

As shown in Fig. 26, different electrical energy storage technologies can be used to achieve intermittent balancing of the electricity supply. This can be from seasonal variations such as days, weeks or months in which case efficiency of the storage plays a crucial role

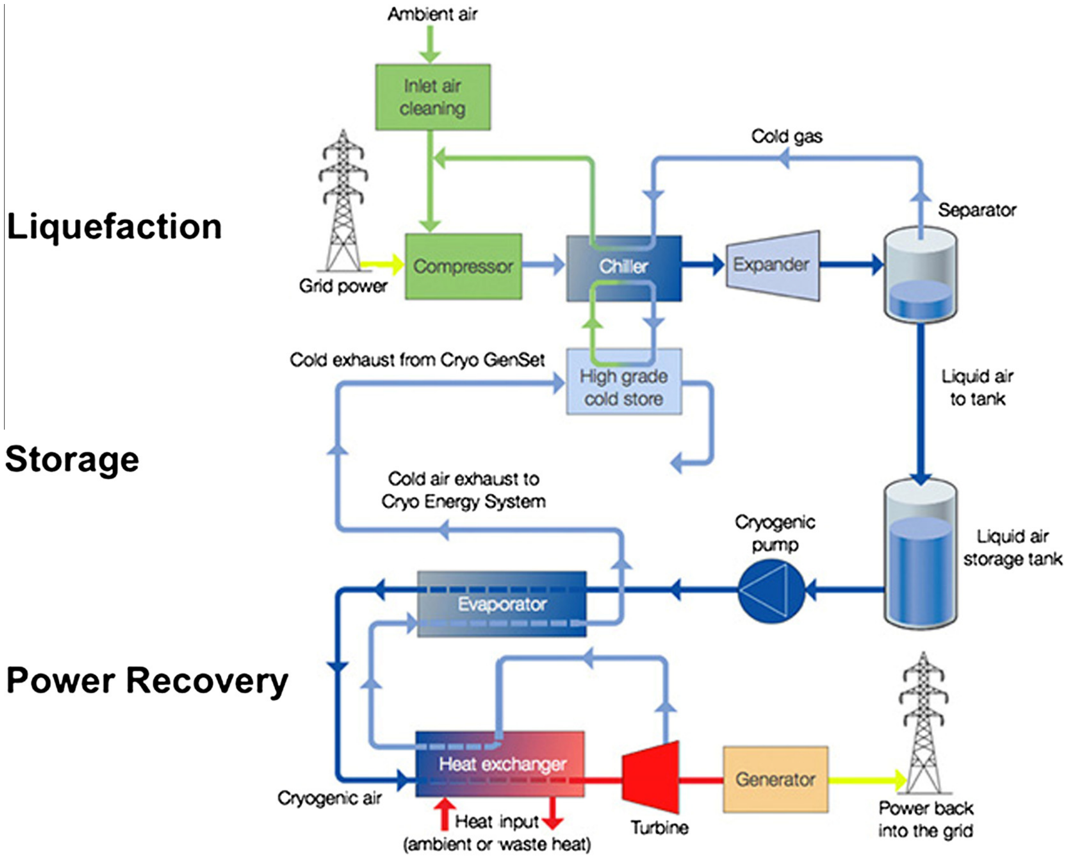


Fig. 25. Highview LAES process [76].

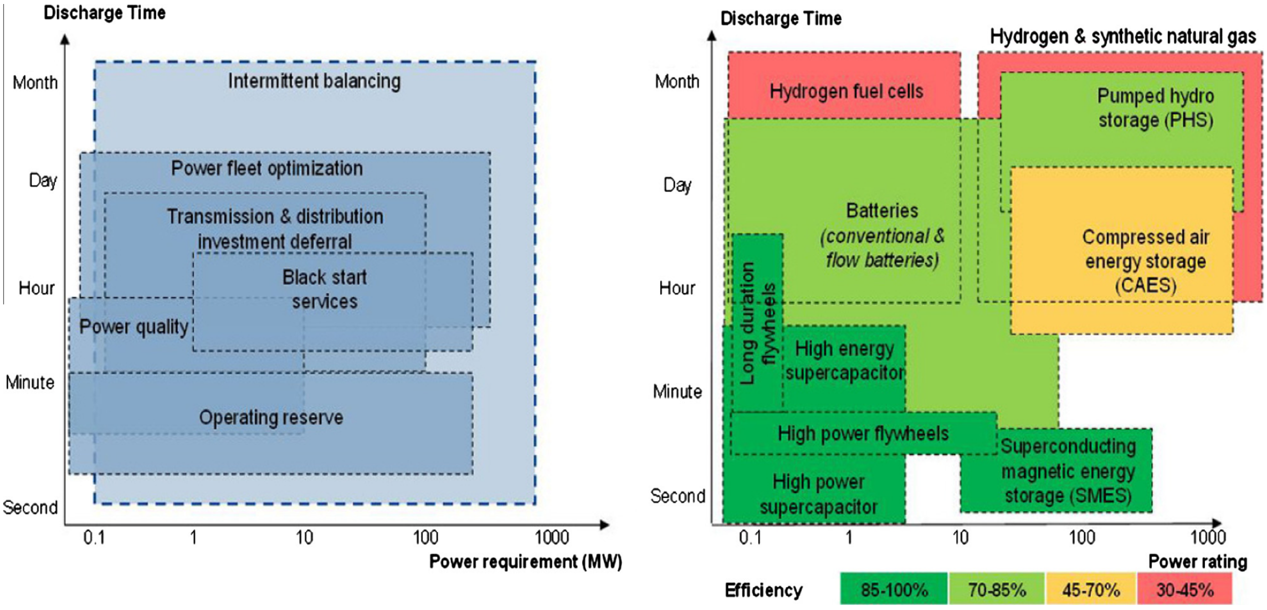


Fig. 26. Real life applications and technology marching [26].

or momentarily such as seconds to minutes as the case with load following, frequency regulation and voltage support in which case the response time is the key requirement. Hydrogen fuel cells, GES, PHS, LAES, CAES and batteries are some of the energy storage technologies which can be utilised for seasonal variations while flywheels, supercapacitors and SMES are ideal applications which require momentarily variations.

4.2.2. Arbitrage

This involves using electrical energy storage technologies to store low priced electricity during periods of low demand and subsequently sell it during high priced periods [77]. This type of storage require technologies which can achieve long storage duration (hours to days) together with high round trip efficiency. Fig. 26 shows that technology such as batteries, CAES, LAES, GES, and PHS can be used to achieve this type of application.

4.2.3. Renewable penetration

This is one of the pioneer applications which are driving the inclusion of energy storage in the modern electricity supply chain. As the penetration of renewable resources (e.g. wind and solar) into the grid energy mix continues increase, energy storage is needed to change and optimise the output from renewable sources so as to mitigate rapid and seasonal output changes which occurs as a result of the intermittency in energy supply from aforementioned renewable resources. The duration of storage and efficiency are among the key characteristics necessary for this type of electrical energy storage technology. Typical examples of electrical energy storage technologies which can be utilised here include: PHS, LAES, CAES, HES, GES, etc.

4.2.4. Black start

This occurs when power system collapse, ancillary mechanisms failed and electricity supply resources are needed to be restarted without pulling electricity from the grid. This type of application requires an electrical energy storage technology which should be able to response quickly and devoid of any energy intensive auxiliary equipment. From Fig. 26, it can be seen that electrical energy storage technologies such as batteries and supercapacitors are capable of achieving this feat.

4.2.5. Mobile application

As the name implied, it covers standalone energy storage in which the device can easily be moved around from one location to another. It usually occurs for off-grid applications. Some typical examples are electric vehicles which uses electrical energy stored in batteries. Hydrogen fuel cell also feats into this application

4.2.6. Demand shifting and peak reduction

This involves shifting energy demand in order to match it with supply. It can be facilitated by changing the time at which certain activities take place (e.g. space heating) so as to reduce the maximum (peak) energy demand level.

4.3. Thermal Energy Storage (TES) and their characteristics

TES is one of the most practiced form of energy storage [78,79]. TES systems consist of devices which are used to store electricity or other waste heat resources in the form of thermal energy pending the time when they are used to meet energy need. There are three thermal energy storage methods [80,81]. They include: sensible heat storage method through a change in material temperature, latent heat storage through phase change of a material and thermochemical heat by thermally inducing changes in a material's chemical structure [25,82–85]. The choice of TES method depends on a variety of factors such as the storage temperature range, the specific application and the storage media. TES systems are generally classified into low-temperature and high temperature systems depending on the whether the operating temperature of the material is higher than the room temperature [12,86]. Low temperature TES are assumed to operate in a temperature range below 200 °C. This set of TES system has been extensively investigated and developed. They are usually found in building heating and cooling application, solar cooking, solar water boiler and air heating system. High temperature TES systems are usually used in renewable energy technologies, waste heat recovery and thermal power systems. As aforementioned, thermal energy can be stored in the form of cryogenic, sensible heat, latent heat or thermochemical means.

4.3.1. Sensible heat storage

In this form of energy storage system, the storage material does not undergo any form of phase change within the temperature range required for the storage application [87]. The most common materials used in this category for high temperature TES include: concrete, cast ceramics and molten salts. Molten salts have been used in solar thermal applications. Their major drawback is that most of them have high freezing point (around 100 °C) which can lead to energy losses. They also recover a fraction of the heat stored during the discharge process due to the irreversibility in the heat exchanger device.

4.3.2. Latent heat storage

As the name implies, these materials store latent heat which occurs as a result of phase change in the storage media. They are usually known as Phase Change Materials (PCMs). For energy storage application, the phase of the material changes (usually from solid to liquid) at a temperature matching the thermal input source [12]. These materials always achieve a high potential for thermal energy storage than the non-phase changing counterpart due to the high latent heat associated with the phase change. They are classified into organic PCM and inorganic PCM. The organic PCM are classified into paraffin and non-paraffin PCM. Paraffin wax represents a good example of paraffin PCM [9]. It is made of a mixture of mostly straight-chain *n*-alkanes ($CH_3–(CH_2)_n–CH_3$). Non-paraffin PCM includes fatty acids, esters and glycols. Inorganic PCM include salt hydrates, salts, metals and alloys. Examples are sodium sulphate decahydrate, calcium chloride hexahydrate, sodium thiosulphate, etc.

4.3.3. Thermochemical heat storage

As shown in Fig. 27, this form of heat storage involves a reversible reaction in which heat is stored during the endothermic reaction step and released during the exothermic one [22]. During the charging step, thermal energy is used to dissociate a chemical reactant into products in a reaction which is endothermic. The products are stored separately pending when energy is needed. During the discharging step, the stored products are mixed together and react to form the initial reactant in a reaction which is exothermic. The heat released during the reaction is utilised as an energy source.

This type of TES is still mainly in the research and development stage with many materials been investigated. Examples of some

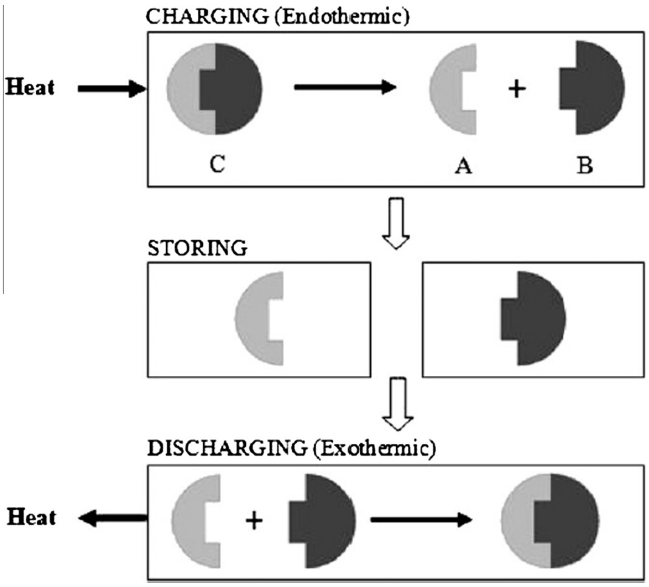


Fig. 27. Process of thermochemical heat storage [12].

thermochemical TES material currently been investigated include: metallic hydrides (MgH_2 and CaH_2), carbonates ($PbCO_3$ and $CaCO_3$), hydroxides ($Mg(OH)_2$ and $Ca(OH)_2$), oxides (BaO_2 and Co_3O_4), ammonia system (NH_4HSO_4 and NH_3), and organic systems (CH_4/H_2O, CH_4/CO_2, C_6H_{12}). They have potentials over the sensible and latent heat systems. Their energy density is about 5–10 times higher than latent and sensible heat storage systems respectively; their storage period and transport are theoretically unlimited because there is no thermal loss during storage as products can be stored at ambient temperature [9,88].

4.4. Thermal energy storage technologies and real life applications

4.4.1. Waste heat utilisation

Thermal energy storage technologies can be used for the temporal and geographic decoupling of heat supply and demand [77]. Typical examples are the hot and ice/chilled water storage which is used for heating and cooling application and supply of industrial process heat.

4.4.2. Combined Heat and Power (CHP)

Thermal energy storage can be utilised to increase the operational flexibility of CHP plants. It can be used to decouple the heat demand of a connected district heating system and the requirements of the electricity system. As a result of this increased flexibility, the CHP can be operated as a load following with minimal need for complex control system.

5. Comparison of different ES technologies

Any given energy storage technology has some unique features/characteristics which make it suitable for a particular energy storage application. These unique features help in the determination of the best energy storage technology to be adopted in any given circumstance. Some of these features are explained in this section. The technical details of these characteristics for the different energy storage technologies are summarised in Table 2.

5.1. Energy/power density

The power density of any energy storage technology is defined as the rated power output divided by the volume of the device [9,12]. Its unit is W/kg or W/l. This is slightly different from the energy density which is defined as the actual energy stored divided by the volume of the storage device (W h/kg or W h/l). In these definitions, the volume of the device is regarded as the volume of the whole energy storage system including the energy storing element, accessories, supporting structures and inverter systems [12]. ES systems with very high power density are usually suitable for applications which require high power quality with large discharge currents and fast response time. As shown in Table 2, HES and Zn-Air battery have very high energy density but suffer from low round trip efficiency. Other conventional batteries, CAES and LAES follow with medium energy density while PHES, SMES, flywheel and supercapacitors have lower energy density. Amongst the batteries, Li-ion, NaS and $NaNiCl_2$ have higher energy density than the others. Flow batteries also show a lower energy density than the conventional batteries.

5.2. Life time

The life span any given energy storage technology also plays a significant part in deciding whether the technology will be adopted for any given application or not. All things been equal, energy storage technologies with long life span are usually preferred from an investment point of view over those with short life span. From Table 2, it can be affirmed that mechanical energy storage technologies which are based on conventional mechanical engineering such as PHES, CAES, flywheel, gravity energy storage and hydrogen energy storage systems usually have long life time as their life time is mainly determined by the life time of the mechanical components. Even though there is currently no reliable data for some of the technologies that are still in the concept or demonstration stage such as LAES, GPM, ARES, operational experience from mechanical components which make up the system also suggest that they will likely have long life time when fully matured. Battery based systems usually have short life time owing to chemical deterioration with the operating time.

5.3. Capital and operating costs

The cost of an energy storage technology is one of the most important factors for commercial deployment of a given energy storage technology. For detailed analysis, the cost of any given energy storage technology should include both the capital and operating costs. The operating cost covers the cost of operation, maintenance, disposal and replacement. The auxiliary components used by some energy storage technologies add to the total capital cost of the system. As a result of this, some energy storage systems tends to be only economically feasible above a minimum energy content and power output [9]. There are various ways in which the costs can be calculated. They include cost per kW h, per kW and per kW h per cycle. The later is preferred for systems with frequent charge/discharge application. In terms of capital cost per kW h, PHES, CAES, Zn-Air are in the low range. Unproven and promising technologies such as GPM and ARES are expected to have capital cost per kW h in the same or slightly higher order of magnitude as the PHES when fully matured as they are based on similar concept. LAES, which is currently in the demonstration stage, is also a promising technology for low capital cost. Table 2 shows that CAES has a lower capital cost per kW h than the PHES but also suffers from low round trip efficiency. Flywheel, SMES, supercapacitors have very high power density and capital cost per kW h but low capital cost per kW h per cycle which makes them suitable for applications that require high power output for short duration.

5.4. Storage capacity/duration

This refers to the quantity of energy available in the storage device. In other words, it is the total energy stored in the energy storage device. Its unit is Wh. It is different from the energy retrieved from the storage device since discharge is usually incomplete. Commercial scale energy storage devices usually have large storage capacity. Due to self-discharging problem, storage duration is also regarded as one of the essential feature to be considered while deciding on an energy storage technology to deploy for any given application. It shows how much of the stored energy can be retained by the energy storage device for over a period of time. Devices with very low self-discharging ratio are usually suitable for long storage applications. From Table 2, PHES and CAES have large storage capacity and thus are suitable for grid scale energy storage application. Developing technologies such as LAES and other technologies which are in the concept stage such as GPM and ARES are likely to be suitable for grid scale applications as they are scalable and also based on matured mechanical components. These technologies are also suitable for long duration storage since they have low self-discharge rate.

Table 2
Technical characteristics of some selected energy storage technologies.

Technology	Energy density Wh/kg(W h/L)	Power density W/kg(W/L)	Power rating	Discharge time	Suitable storage duration	Life time (years)	Cycle life (cycles)	Capital Cost			Round trip efficiency (%)	Technological maturity
								$/kW	$/kWh	$/kW h-per cycle		
Flywheel	10–30(20–80)	400–1500(1000–2000)	0–250 kW	ms–15 min	s–min	~15	20,000+	250–350	1000–5000	3–25	85–95	Commercial
PHES	0.5–1.5(0.5–1.5)		100–5000 MW	1–24 h+	h–months	40–60		600–2000	5–100	0.1–1.4	65–87	Matured
CAES	30–60(3–6)		5–300 MW	1–24 h+	h–months	20–60		400–800	2–50	2–4	50–89	Developed
GES												
GPM	1.06(1.06)	3.13(3.13)	40–150 MW		h–months	30+		1000			75–80	Concept
ARES			100–3000 MW	34 s	h–months	40+		800			75–86	Concept
HES												
Fuel cell	800–10,000(500–3000)	500+(500+)	0–50 MW	s–24+h	h–months	5–15	1000	10,000+		6000–20,000	20–35	Developing
Gas engine	33,300(530–750)		0–50 MW	s–24+h	h–months						40–50	Developing
Super-capacitor	2.5–15	500–5000	0–300 kW	ms–60 min	s–h			100–300	300–2000	2–20	90–95	Developed
Batteries												Commercial
NaS	150–240(150–250)	150–230	50 kW–8 MW	s–h	s–h	10–15	2500	1000–3000	300–500	8–20	80–90	Commercial
NaNiCl	100–120(150–180)	150–200(220–300)	0–300 kW	s–h	s–h	10–14	2500+	150–300	100–200	5–10	85–90	Commercial
VRB	10–30		30 kW–3 MW	s–10 h	h–months	5–10	12,000+	600–1500	150–1000	5–80	85–90	Demonstration
FeCr	10–50	16–33	5–250 kW	s12+h	h–months				250		70–80	Commercial
ZnBr	30–50(30–60)		50 kW–2 MW	s–10 h	h–months	5–10	2000+	700–2500	150–1000	5–80	70–80	Demonstration
Zn-air	150–3000(500–10,000)	100	0–10 kW	s–24h+	h–months			100–250	10–60		50–55	Demonstration
Li-ion	75–200(200–500)	500–2000	0–100 kW	min–h	min–days			1200–4000	600–2500	15–100	85–90	Demonstration
SMES	0.5–5(0.2–2.5)	500–2000(1000–4000)	100 kW–10 MW	m–8 s	min–h	20+	100,000+	200–300	1000–10,000		95–98	Demonstration
LAES	97		350 kW–5 MW	1–24 h+	h–months	20+		1000–2000			50–70	Demonstration

5.5. Round trip efficiency

The round trip efficiency is the ratio of the electricity output from the storage device to the electricity input to the device during one charge/discharge cycle. It accounts for the losses which occur as a result of storing and withdrawing energy from the energy storage device. Some of the energy losses occur in the auxiliary devices used in the energy storage process. As shown in Table 2, SMES, flywheel, supercapacitors and Li-ion battery have very high efficiency (>90%). These are followed by PHES, CAES, batteries (50–90%) and then HES, Zn-air battery technologies which have low round trip efficiency (<50%). Promising technologies such as gravity based technologies (GPM and ARES) are projected to have efficiencies similar to PHES when fully matured while LAES is tipped to have an efficiency >70% depending on the plant configuration and waste heat availability.

5.6. Response time

Depending on the energy system requirement, some applications may require a very fast release of the stored energy to meet the system energy demand. For example, most power quality maintenance such as instantaneous voltage drop and flicker mitigations requires response time in the order of milliseconds. This limits the types of energy storage technologies that can be considered for such application. From Table 2, supercapacitors, SMES and flywheel have very fast response time in the order of milliseconds. This is followed by batteries with response time in order of seconds, then PHES and CAES in minutes.

5.7. Technological maturity

Technological maturity of any energy storage system plays a significant role in determining whether it should be selected for any given energy storage application. Matured technologies are usually preferred because more operational expertise has been developed in its operation than for less matured counterparts. Furthermore, increase in the maturity always drives down the cost of any given technology. From Table 2, PHES and lead-acid battery are the most matured energy storage technology. CAES is developed but there is still a need for improvement in its round trip efficiency which is the mainstay of many current researches in CAES systems. Other technologies such as NaS, $NaNiCl_2$, flow batteries, Li-ion SMES, flywheel, supercapacitors are also developed and are commercially available but mainly in demonstration projects. Their application for large-scale energy storage is highly uncommon. HES, Zn-Air battery are in the developing stage with few demonstration plants in operation. LAES is still in the demonstration stage while GPM and ARES are in the concept stage of development with no record of operation available for now.

6. Current status and some real life ES projects

In the traditional electricity value chain, energy storage was not considered as a valuable component [12]. This is partly because electricity generation were based on fossil fuels which are reliable and stable. The lack of interest in energy conservation and greenhouse gas emission reduction also contributed to the lack of interest in energy storage as a valuable link in the traditional electricity value chain. Nowadays, due to the increase in the number of intermittent renewable energy resources, the need to conserve the exhaustible fossil fuel resources, to reduce the greenhouse gas emission and supply power when and where needed, energy storage is now considered an integral part of the modern electricity value chain.

Globally, various kinds of energy storage projects have been executed at varying scales as shown in Table 3. A detailed analysis of the global energy storage project database of the United States Department of Energy [89] reveals the following:

- The battery energy storage technology has the most number of operational projects followed by PHES and then the thermal system as shown in Fig. 28.
- In terms of the quantity of energy stored, pumped hydro represents about 98%, followed by thermal which has about 1% and then flywheel with approximately 1% (see Fig. 29).

Fig. 30 shows in terms of the quantity of energy stored; that the open loop system represents about 99% of the global operational pumped hydro energy storage while closed loop system represent only 1%.

Hence, open loop pumped hydro system seems to be more favourable option than the closed loop system as reflected in the project share of the former over the later (see Fig. 31).

As shown in Fig. 32, the most common form of operational battery energy storage technology is Li-ion battery followed by the Li-ion phosphate battery and then sodium sulphur, vanadium redox flow and lead acid battery in that order. Despite the large quantity of Li-ion used for battery based energy storage projects, it represents only about 18% of the quantity of energy stored using battery energy storage systems (see Fig. 33). This confirms the fact that Li-ion battery is usually used for portable energy storage application. On the other hand, NaS battery contributed about 24% of the quantity of energy stored using battery technology showing that it is used for large scale energy storage application. Advanced lead acid battery also contributed about 18% of the operational battery energy storage globally just from 15 projects confirming its suitability for large scale energy storage applications.

Figs. 34 and 35 show the number of different operational thermal energy storage projects globally and the corresponding share of each of the technology in terms of the actual quantity of energy stored. The figures show that ice thermal energy storage technology remains the most implemented thermal energy storage technology globally followed by molten salt, chilled water and then heat. Ice thermal energy storage is usually used for time shifting small scale applications to provide air conditioning during peak periods. Molten salt thermal energy storage are used for high temperature large scale application as found in solar thermal power plants or any other high temperature application. This fact is also confirmed in Fig. 33 which shows that molten salt technology represents about 77% of the quantity of energy stored as thermal energy.

The analysis also shows that there is currently no operational thermochemical energy storage system although this technology is believed to have some potential for large scale applications. In the case of CAES technology, in-ground natural gas combustion technology is the most used technology as seen in Fig. 36. The Huntorf and the McIntosh CAES are currently the only two commercially operational in-ground natural gas energy storage systems in the world. The in-ground isothermal and modular isothermal technologies are currently emerging for commercial applications. The in-ground natural gas combustion technology is also currently the most used form of CAES technology for large scale application. It accounted for about 99% of the quantity of energy stored using compressed air technology (see Fig. 37). Isothermal option is still an emerging technology and will likely pose a better efficiency than the compressed air technology due to its more efficient compression operation.

Table 3
List of some operational energy storage projects.

Technology	Project name	Location	Construction start year	Construction duration	Rated power (MW)	Duration at rated power	Mode	Status	Source
Pumped Hydro Energy Storage									
Open loop	Bath county pumped hydro storage	Virginia, USA	1977	8 years	3030	10 h 18 min	Commercial	Operational	[90]
Open loop	Olivenhain–Hodges storage plant	California, USA	2005	7 years	40	6 h	Commercial	Operational	[91]
Open loop	John W. Keys III pumped generating plant	Washington, USA	Used initially for irrigation but, converted to power plant in 1960	13 years	314	80 h	Commercial	Operational	[92,93]
Open loop	Helms pumped hydro storage	California, USA	1977	7 years	1212		Commercial	Operational	[94]
Open loop	San Luis (William R. Gianelli) pumped storage	California, USA	1962	6 years	424	298	Commercial	Operational	[89]
Open loop	Drakenberg pumped storage	Kwa-Zulu Natal, South Africa	1974	7 years	1000	10 h	Commercial	Operational	[89]
Flywheel energy storage									
	Beacon Power flywheel frequency regulation plant	Pennsylvania, United States	2013	1 year	20	15 min	Commercial	Operational	[95]
	Max Planck Institute Power Supply System	Bavaria, Germany	EZ1, 1973 EZ2, 1977 EZ3, 1987	1 year 1 year 1 year	155 124 108	12 s	Commercial	Operational	[89]
	EFDA JET fusion flywheel	Oxfordshire, United Kingdom	1981	1 year	400	50 s	Commercial	Operational	[96]
Thermal energy storage									
Heat (steam) thermal	Planta solar 20 solar power plant	Seville, Spain	2006	3 years	20	1 h	Commercial	Operational	[97]
Heat (steam) thermal	Julich solar tower	Rhineland, Germany	2007	1 years	1.5	1 h 30 min	Demonstration	Operational	[98]
Heat (steam) thermal	Minera El Tesoro CSP	Atacama, Chile	2011	1 year	10.5	6 h 30 min	Commercial	Operational	[89]
Ice thermal	Glendale water and power – peak capacity project	California, USA	2010	1 year	1.5	6 h	Commercial	Operational	[99]
Molten salt thermal (60% sodium nitrate, 40% potassium nitrate)	Manchasol 2 solar (power plant	Ciudad Real, Spain	2008	3 years	50	7 h 30 min	Commercial	Operational	[89]
Battery energy storage									
Lead-acid	STMicroelectronics UBS system	Arizona, United States	2001	8 months	10	50 s	Commercial	Operational	[89]
Lithium-ion	AES angamos storage array	Antofagasta, Chile	2008	3 years	20	20 min	Commercial	Operational	[89]
Nickel-cadmium	GVEA battery energy storage	Alaska, United States	2003	1 year	27	15 min	Commercial	Operational	[100]
Sodium-sulphur	AEP presidio NaS energy storage system	Texas, United States	2009	7 months	4	8 h	Commercial	Operational	[89]
Vanadium redox	Tomamae wind farm	Hokkaido, Japan	2005	1 month	4	1 hr 30 min	Commercial	Operational	[89]
Compressed air energy storage									
In-ground natural gas combustion compressed air	McIntosh CAES plant	Alabama, United States	1988	2 years 6 months	110	26 h	Commercial	Operational	[101]
In-ground natural gas combustion compressed air	Kraftwerk Huntorf	Elsfleth, Germany			321	2 h	Commercial	Operational	[102]
In-ground isothermal compressed air	Texas dispatchable wind	Texas, United States	2011	1 year	2	250	Commercial	Operational	[103]

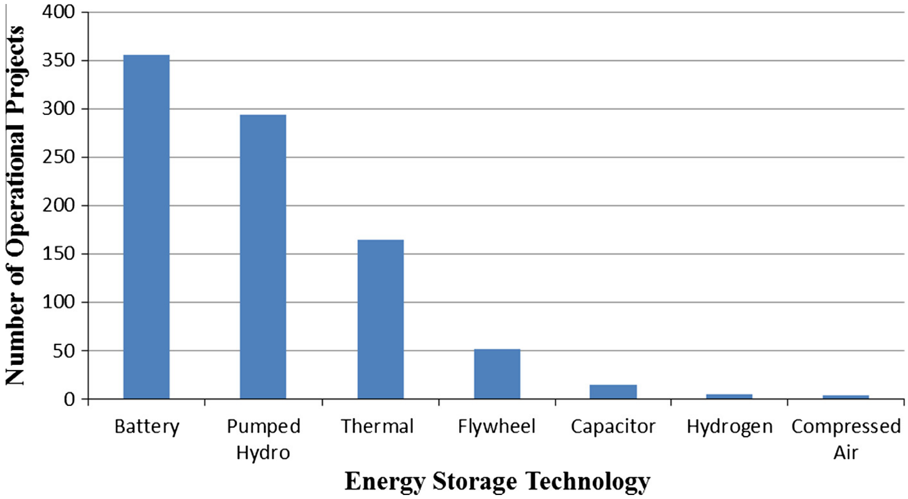


Fig. 28. Number of operational projects.

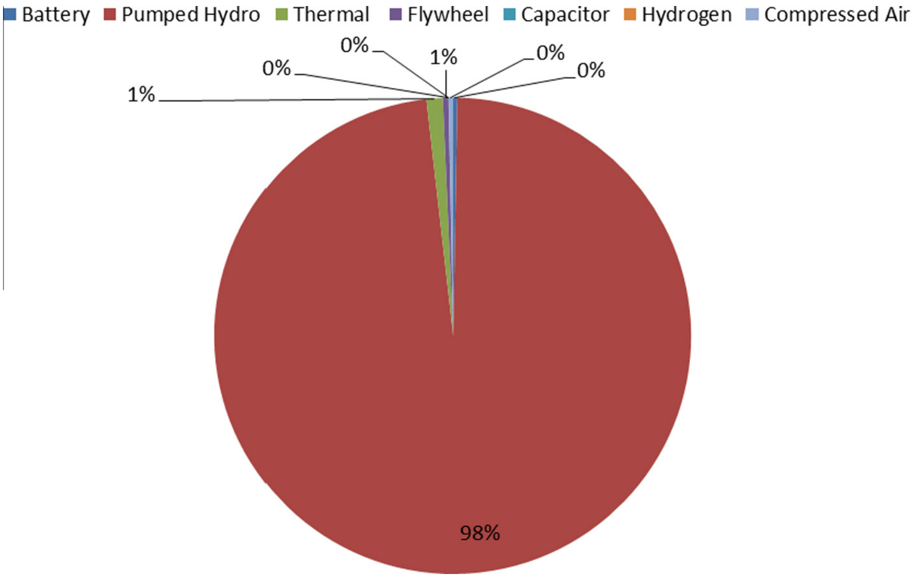


Fig. 29. Technology share of quantity of energy stored globally.

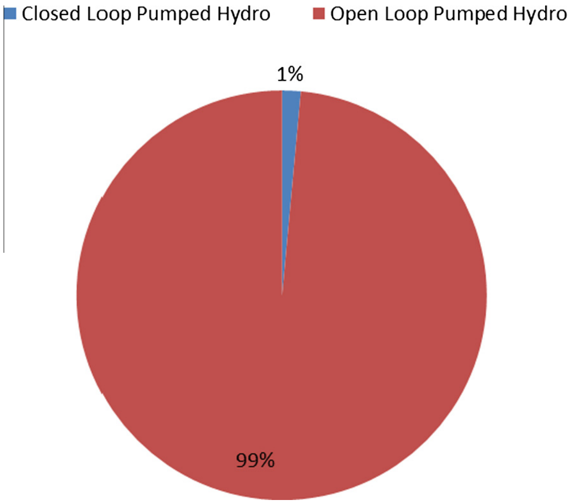


Fig. 30. Technology share of the quantity of energy stored using pumped hydro system.

7. Challenges & future prospects

It is no doubt that energy storage can help to reduce energy wastage and greenhouse gas emissions as well as to increase the penetration of renewable energy resources. As presented in previous sections of this paper, several energy storage projects have been executed to prove some of the energy storage technologies and concepts. Some of these projects, as already seen in this review, have been successful. For example, the pumped hydro and compressed air technology have been used for decades with proven reliability and availability. Advancement in battery technology has resulted in more robust and efficient battery technologies with high power and energy density.

Despite all these advancements, energy storage is still being faced by enormous challenges:

(1) One of the main challenges (especially of large scale energy storage technologies such as PHES and CAES) is how to improve the round trip efficiency. An ideal energy storage

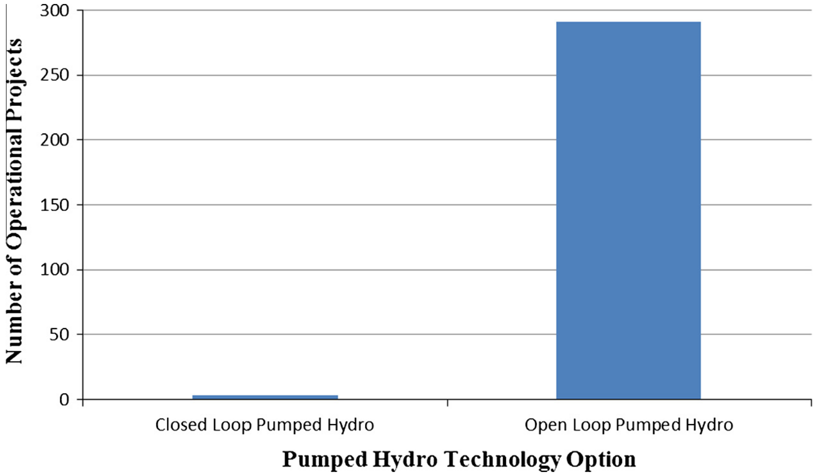


Fig. 31. Pumped hydro technology options.

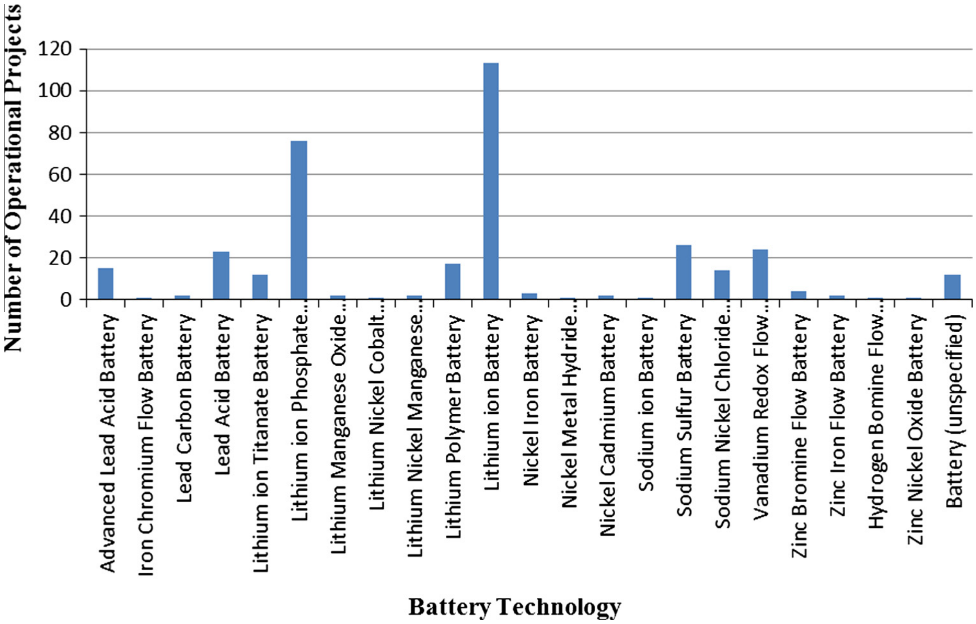


Fig. 32. Battery energy storage technology options.

technology is one which can achieve a round trip efficiency of 100%. Although this is not possible in real life application, notwithstanding, an energy storage technology should aspire to achieve round trip efficiency as close as possible to 100% so as to reduce the gap between their potential and operational success. Theoretical prediction for PHES show that they can potentially attain an efficiency of 90%, however, most of the real life installations have shown a round trip efficiency of 72–75%. In the same vein, CAES shows an efficiency of about 42–55%. The challenge lies in identifying how to improve these efficiencies.

(2) Another challenge is that of the system economics. The economics of energy storage are difficult to evaluate since they are influenced by a wide range of factors: the type of storage technology, the requirement of each application, size and the system in which the storage facility is located [26]. Most of the energy storage technologies are still very expensive whereas the incentive lies in making these technologies cheap. The reason is because energy storage technologies are usually used to store electricity which is a relatively cheap commodity and thus for these technologies to be economically viable and attractive to investors, it need to be cheap as well. Fig. 38 shows the capital costs of different energy storage technologies per unit of power ($/kW) and per unit of energy capacity ($/kW h).

From the figure, it can be seen that the costs varies significantly from one technology to another. The figure also shows that for power driven applications, flywheel and supercapacitors shows low capital cost per unit of power but high investment in energy capacity. In contrast, CAES and PHS have relatively high capital costs per unit of power but low cost per unit of energy. Apart from the capital cost, there are other costs which make up

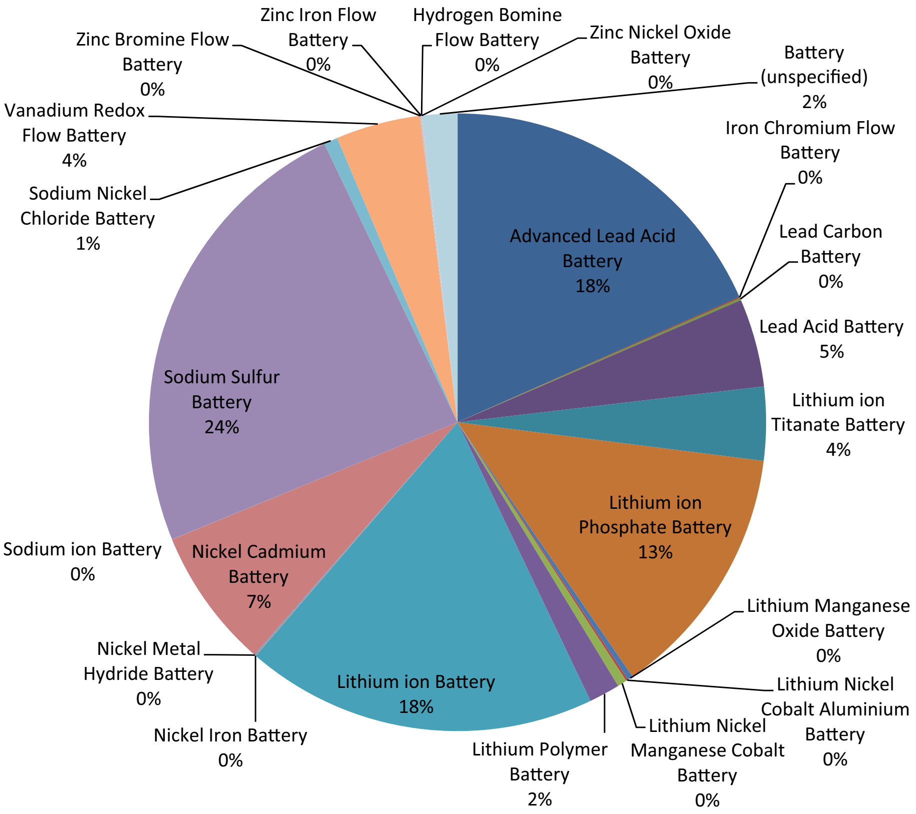


Fig. 33. Technology share of the quantity of energy stored using battery system.

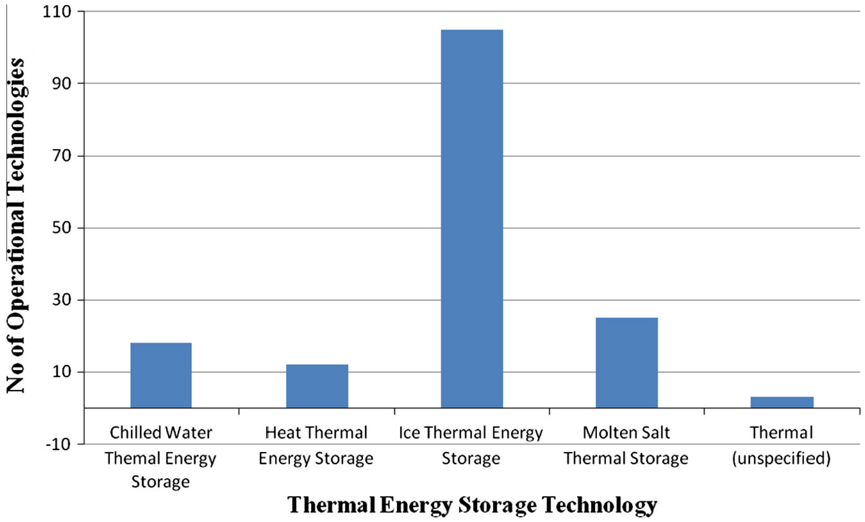


Fig. 34. Thermal energy storage technology options.

this storage total operating cost. These costs consist of two key components: (1) energy-related cost and (2) non-energy related operating cost [104]. The energy related costs includes all costs incurred to purchase energy used to charge the storage as well as the cost to purchase energy needed to make up for the energy losses arising from round trip efficiency whereas the non-energy related costs include the labour cost associated with plant operation, the frequency of charging and discharging cycles, the plant maintenance cost, costs associated to equipment depreciation, decommissioning and disposal cost [104]. These costs vary widely from one energy storage technology to another as well as the size of the storage system. For example large scale PHS and CAES may require labour cost to operate while a small scale battery system that was designed for autonomous operation may require no labour cost. Hence, an energy storage technology for high-use application is ideally required

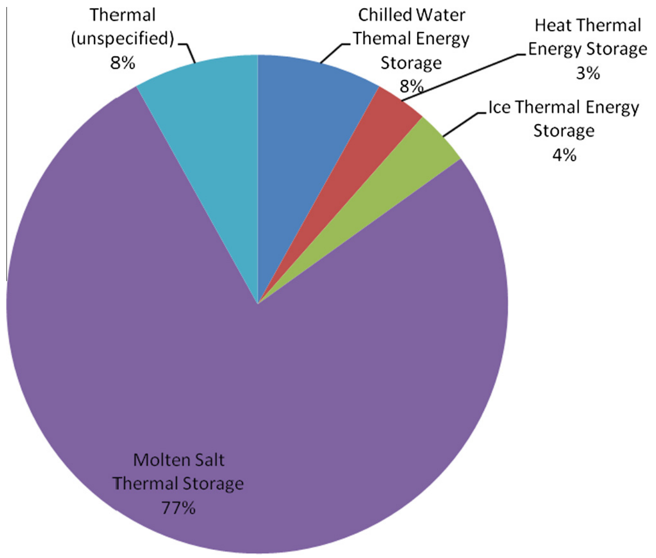


Fig. 35. Technology share of the quantity of energy stored using thermal system.

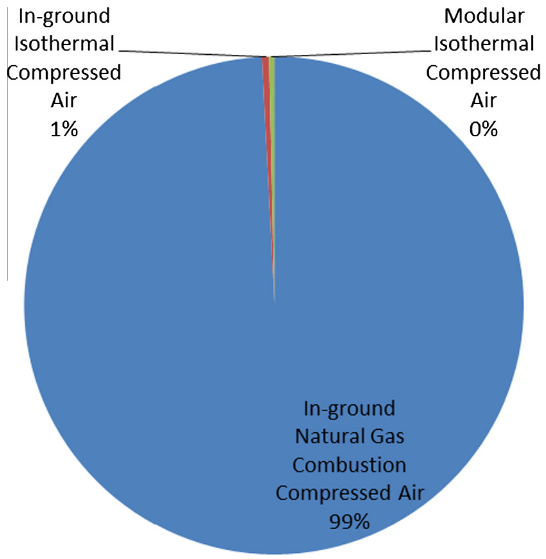


Fig. 37. Technology share of the quantity of energy stored using compressed air technology.

to have relatively very high efficiency and low variable operating cost otherwise the total cost to charge and discharge the storage might likely be higher than the benefit. Overall, CAES and PHS are the most cost-effective technologies for large scale storage with frequent cycles, flywheel and supercapacitors will be preferred for very short periods and frequent use whereas batteries are likely to be the cheapest solution when the number of cycles is low [26].

(3) The third challenge faced by this sector is the unavailability of standard for the physical connections of different energy storage solutions to the electricity grid. There is still too much complexity in the entire design of some energy storage technologies which makes it difficult to develop modular energy storage systems. Although some energy storage technologies such as batteries are already standardised and modularised, most of the other energy storage technologies have still not achieved this feat. Modularisation of the energy storage technologies helps to promote the flexibility that the system provides. It allows for more optimisation of the system behaviour in response to changing conditions.

(4) In addition to the aforementioned challenges, for energy storage to prosper; there is also a need for policy support from the Government. This will enhance the penetration of energy storage especially for grid application. For example, the UK electricity grid is estimated to reach 110 GW by 2020 and the government aims to generate 30% of this energy from renewable. The government is currently funding energy storage research so as to achieve this aim.

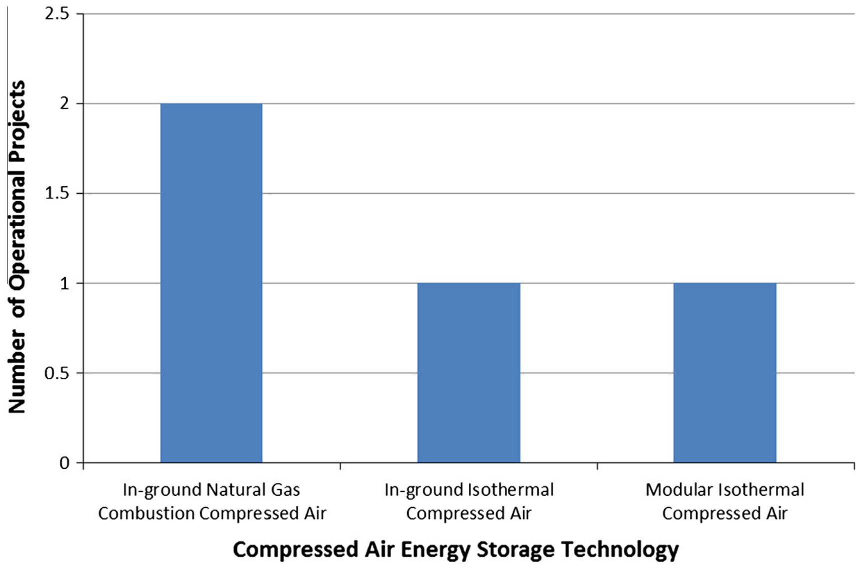


Fig. 36. Compressed air energy storage technology options.

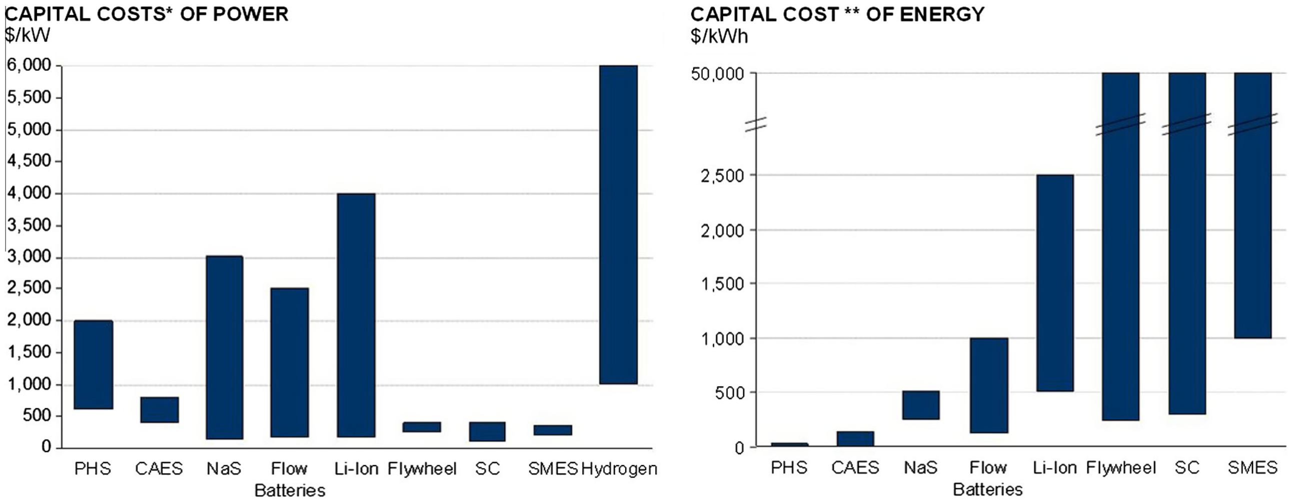


Fig. 38. Capital cost of energy storage per unit power and per unit energy capacity [26].

8. Conclusions

In this review paper, two different forms of energy: primary and secondary energy forms were introduced. Different technologies for storing the aforementioned energy forms with emphasis on secondary energy forms (electricity and heat) were presented. The different energy storage technologies were compared technically and their real life application analysed so as to understand the most widely applied technology in terms of scale, number of operational project and level of maturity. Some challenges facing the energy storage industry as well as the future prospects of the sector were also presented.

Based on the review, the following conclusions were arrived at: (1) Many energy storage solutions are available but they are so different in terms of specifications and characteristics which make it difficult to select a single technology for all energy storage applications. Thus, this review paper focused on the number of real life operation of each of the technology together with the quantity of energy stored with such technology. This real life application helps in understanding the actual level of penetration of the technologies. (2) Some energy storage technologies such as supercapacitors, thermochemical, and gravity are either in the demonstration or research stage and hence there are yet no large scales real life projects to ascertain their capability for energy storage application. More research is therefore necessary as there is no one energy storage technology that has all characteristics required for optimal operation. (3) Emerging technologies such as LAES, GPM and ARES have potentials for large scale application when fully matured. (4) If GPM achieves the claimed round trip efficiency (75–80%) when matured, it can be a good alternative to PHES in locations without favourable topography. (5) ARES can become a good alternative to PHES for large scale application in locations with the necessary topography but without adequate water supply. (6) Further research and development is required for HES to improve their round trip efficiency. (7) Molten salts will continue to dominate the thermal energy storage sector for large scale application while PHES is expected to still maintain a large share of quantity of energy stored.

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