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Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications

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ABSTRACT

Renewable Energy Sources have been growing rapidly over the last few years. The spreading of renewables has become stronger due to the increased air pollution, which is largely believed to be irreversible for the environment. On the other hand, the penetration of renewable energy technologies causes major problems to the stability of the grid. Along with the fluctuations of the renewable energy technologies production, storage is important for power and voltage smoothing. Energy storage is also important for energy management, frequency regulation, peak shaving, load leveling, seasonal storage and standby generation during a fault. Thus, storage technologies have gained an increased attention and have become more than a necessity nowadays. This paper presents an up to date comprehensive overview of energy storage technologies. It incorporates characteristics and functionalities of each storage technology, as well as their advantages and disadvantages compared with other storage technologies. Comparison tables with several characteristics of each storage method are included, while different applications of energy storage technologies are described as well. Finally, several hybrid energy storage applications are analyzed and different combinations of energy storage technologies are reviewed.

1. Introduction

Renewable Energy Sources (RES) have been growing rapidly over the last few years. The spreading of renewables has become stronger due to the increased air pollution, which is largely believed to be irreversible for the environment [1]. Moreover, the depletion of fossil fuel resources, the increased oil prices and the growth in electricity demand are important factors for the growing attention in RES. In addition to that, buildings in Europe are responsible for the 40% of the total EU energy consumption, and as a result they contribute to greenhouse gas emissions and, possibly, to climate change. Therefore, the reduction of the energy consumption and the use of RES in buildings are believed to have a positive impact on climate and gradual independency on conventional fuels [2,3].

On the other hand, the penetration of renewable energy technologies causes major problems to the stability of the electrical grid. This happens because renewable energy production cannot be predicted accurately, as it relies on weather conditions such as sunlight and wind. For instance, when the clouds suddenly appear or the wind stops blowing then the energy production from photovoltaics and wind turbines will be decreased dramatically. Thus, energy storage can allow energy to be stored during high renewable generation or low demand periods, and to be used during low renewable production or high demand periods [4]. Along with the fluctuations of the renewable energy technologies production, storage is important for power and voltage smoothing. Energy storage is also important for energy management, frequency regulation, peak shaving, load leveling, seasonal storage and standby generation during a fault. Thus, storage technologies have currently gained an increased attention and have become more than a necessity [5].

The various storage technologies are in different stages of maturity and are applicable in different scales of capacity. Pumped Hydro Storage is suitable for large-scale applications and accounts for 96% of the total installed capacity in the world, with 169 GW in operation (Fig. 1). Following, thermal energy storage has 3.2 GW installed power capacity, in which the 75% is deployed by molten salt thermal storage technology. Electrochemical batteries are the third most developed storage method with 1.63 GW global power capacity, followed by

Abbreviations: CAES, Compressed Air Energy Storage; CES, Cryogenic Energy Storage; CSP, Concentrated Solar Power; DoD, Depth-of-Discharge; EES, Electrical Energy Storage; FES, Flywheel Energy Storage; PCM, Phase Change Materials; PHS, Pumped Hydroelectric Storage; PSB, Polysulfide bromide battery; RES, Renewable Energy Sources; SMES, Superconducting Magnetic Energy Storage; TES, Thermal Energy Storage; UPS, Uninterruptable Power Supply; VRB, Vanadium Redox flow Battery; ZBR, Zinc-bromine Battery

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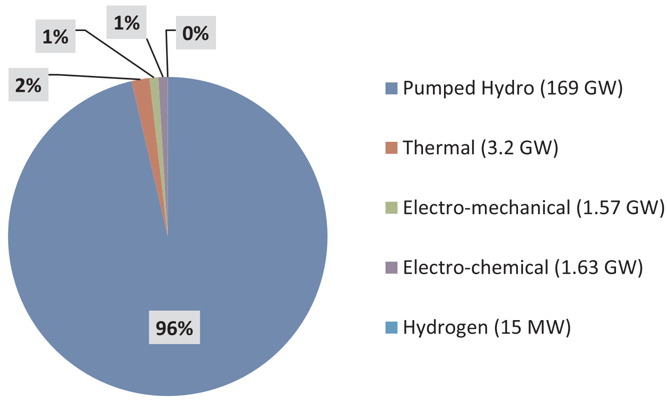

Fig. 1. Global energy storage power capacity by technology group until 2017.

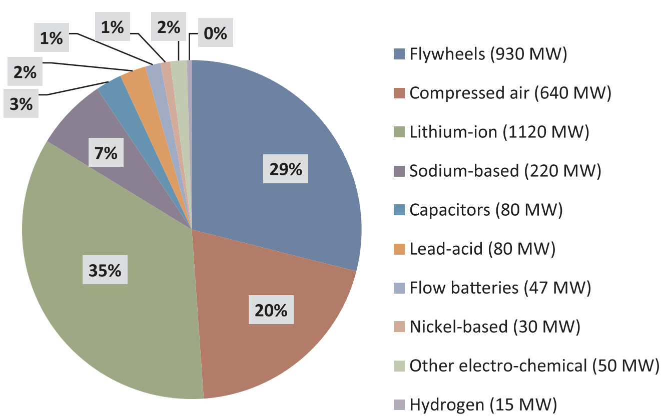

Fig. 2. Global energy storage power capacity shares in MW of several storage technologies until 2017.

electromechanical storage with 1.57 GW global installed power capacity. Finally, a promising energy storage technology is that of hydrogen, which accounts for a small share compared to the above storage groups, with almost 15 MW global installed storage capacity [6–9].

Fig. 2 presents the current global storage shares of electrochemical and electromechanical technologies. Regarding the electromechanical storage, flywheels and compressed air are the most developed storage technologies with storage capacities of 930 MW and 640 MW respectively. However, the storage capacity of flywheel and compressed air storage is concentrated in only three large projects respectively. Lithium-ion batteries account for the largest share of the installed power capacity, with 1.12 GW in operation. The remaining electrochemical technologies are the sodium-based batteries (220 MW), capacitors (80 MW), the lead-acid batteries (80 MW), the flow batteries (47 MW) and the nickel-based batteries (30 MW) [6–9].

This paper analyses all storage technologies, particularly those for electricity generation. Specifically, an updated overview of Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), several types of batteries (lead-acid, nickel-based, sodium-based, lithium-ion, metal-air, redox flow), Hydrogen Storage, Thermal Energy Storage (TES), Superconducting Magnetic Energy Storage (SMES), Flywheel Energy Storage (FES) and Supercapacitors is performed. The main aim of this paper is to present an updated comprehensive overview of the above storage technologies, focusing on their functionalities and characteristics with graphical representation of their operation.

For clarity, a brief explanation of several key terms regarding the characteristics of energy storage technologies is given in the sequel. Firstly, the self-discharge rate indicates the percentage of discharge during a period that a storage method is either not in use or in an open-circuit condition. The response time of a storage method is the duration of time for the transition from no discharge state to full discharge state. Furthermore, the cycle life of a storage method is the total number of charge-discharge cycles before it becomes unusable for an application (e.g. when its capacity is reduced dramatically). Additionally, the Depth-of-Discharge (DoD) is the amount (or percentage) of rated capacity that has been used from a battery. On the other hand, the State-of-charge is the complement of Depth-of-Discharge and represents the percentage of the remaining capacity in the battery [10,11]. Finally, a Control and Power Conditioning System (C-PCS) is presented in most of the figures of the energy storage technologies. A Power Conditioning System is a bi-directional system for conversion of power between the grid side and the storage side. The current produced by most of the storage technologies is direct (DC), thus a conversion to alternating current (AC) is necessary to follow the grid requirements (voltage value, phase, frequency) for connection to the grid [12,13].

In Section 2, all energy storage technologies are presented and examined with regard to their characteristics and functionalities, as well as their advantages and drawbacks. Furthermore, Section 3 compares all energy storage technologies by their energy and power density, lifetime in cycles and years, energy efficiency, response time, capital cost, self-discharge rate and maturity. A brief comparison is given by the form of tables. In Section 4, a discussion of the grid scale energy storage applications is presented. Moreover, in Section 5 several hybrid energy storage applications are analyzed. Finally, the conclusions are summed up in Section 6.

2. Energy storage technologies

Electrical Energy Storage (EES) is a process of converting electrical energy into other forms of energy that can be stored for converting back into electrical energy when needed. One can categorize the storage technologies by storage duration (long-term, short-term storage), by the kind of storage (electrical, mechanical, chemical, thermal, etc.) or by other criteria like capital cost, capacity, efficiency and environmental impact. Fig. 3 shows a classification of Energy Storage technologies by

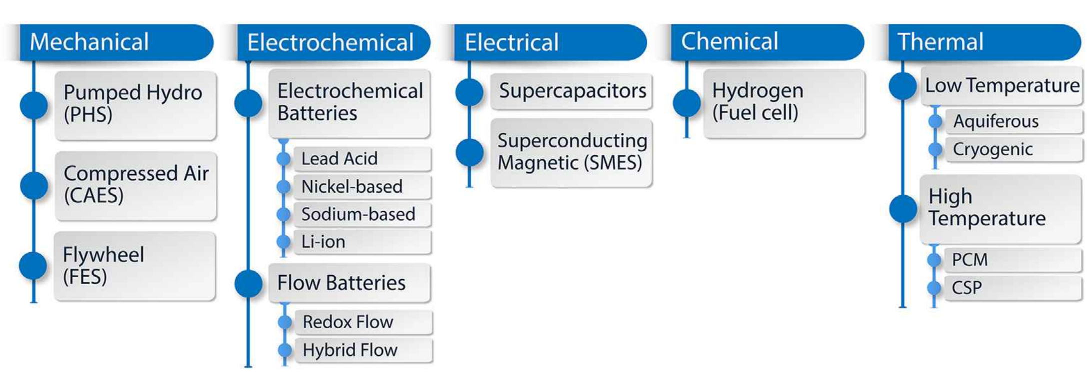

Fig. 3. Classification of energy storage technologies by the form of stored energy.

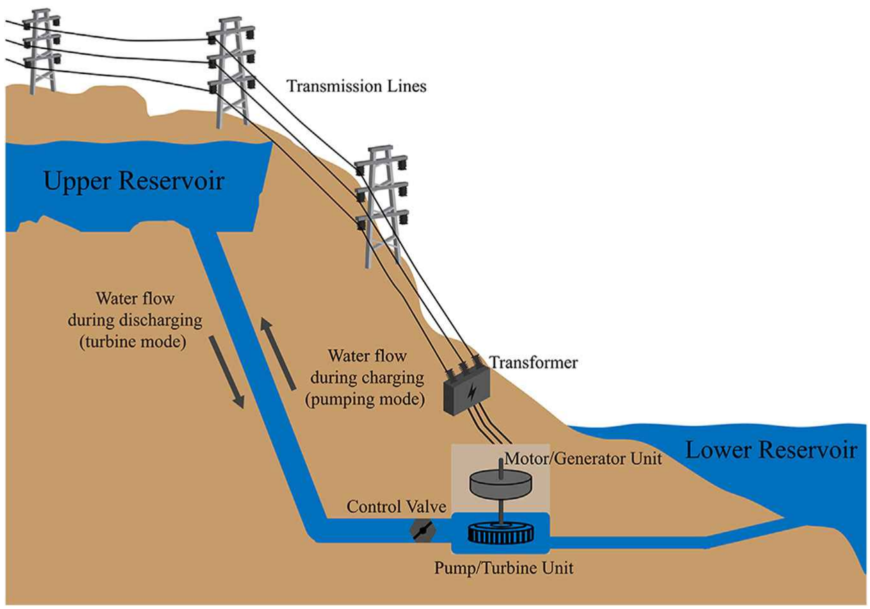

Fig. 4. A typical diagram of PHS system.

the form of stored energy [14].

2.1. Pumped Hydro Storage (PHS)

Pumped Hydro Storage (PHS) is one of the most popular, common and mature methods of storage. PHS is considered as a large-scale energy storage. The first large-scale station for PHS was built in 1929, in Hartford, USA [4]. Currently there are globally over 300 PHS plants with a total installed capacity of 169 GW. The largest PHS plant has a capacity of 3 GW and duration of 10 h at rated power. It was built by the end of 1985 at Virginia, USA [8]. The functionality of PHS is simple. A quantity of water is stored with a large difference in water level (hence, potential energy is present). The water can either flow from upper to lower level or be pumped from the lower to the upper level. During a period of electricity demand, water from the upper reservoir is released and activates the turbines for electricity generation. When there is no need for electricity, the water is pumped to the upper reservoir [15].

As shown in Fig. 4, the PHS system consists of two reservoirs in different levels and a unit to pump water to the upper reservoir in order to convert electricity to potential energy, as mentioned above. Also, there is a turbine to generate electricity when needed. The amount of stored energy is proportional to the quantity of water that can be stored and the height difference between the two levels ($E = mgh$). The lower reservoir can be the open sea or a lake, but it must be near a hill, natural or man-made [4,16]. Poullikkas [17] states that in order for a PHS to become economically viable, there is a rule of thumb that requires the head to be in excess of 300 m.

Among the advantages of PHS are the relatively high efficiency (65–85%), the long lifetime (30–60 years) and the fast response time (< 1 min). In addition, there can be large power capacity (100–1000 MW), long storage period and low cycle cost ($0.1–1.4/kWh/cycle). The drawbacks include long project lead time (around 10 years), large land area, high capital cost ($500–4600/kW) and environmental impact (due to the cutting of trees). Finally, the difficulty of finding a topographically suitable area with large water capacity is a major disadvantage [4,17–19].

Morabito et al. [20] examined a set-up of a pump as turbine (PAT) in micro-PHS. PAT is a pump in reverse mode and can replace the pump and turbine into a single device [21]. Regarding the maintenance, it is mentioned that PAT has many advantages compared to custom-made turbines. Also, regarding the economic side, PATs are profitable in the power range of 1–500 kW and perform capital payback periods of about two years or less. In the same study, a pilot project of a micro-PHS plant using PAT in Froyennes, Belgium is simulated [20].

2.2. Compressed Air Energy Storage (CAES)

In CAES systems the excess energy is stored mechanically by compressing air in natural or mechanically formed caverns. In the most usual designs the air from the atmosphere is used [22]. CAES is classified as a long-term energy storage method because it can reserve or supply power for days. It is not an independent system and has to be associated to a gas turbine plant. When there is excess energy, or the electricity demand is low, the compressor stores air into a sealed volume to a high pressure. During peak loads or when the electricity price is high, the high-pressured air goes through a turbine to generate power [23]. A typical power capacity of CAES plant ranges between 100 and 300 MW. Currently, there are only two large-scale CAES plants in operation: one in Huntorf, Germany, since 1978 (290 MW) and one in Alabama, USA, since 1991 (110 MW) [24–26]. The total global deployment of CAES has currently reached 640 MW, however it is expected that by the end of 2020 two large-scale CAES plants will be operated with total capacities of 317 MW (Tennessee Colony, Texas, United States) and 300 MW (San Joaquin County, California, United States) [7,8].

Fig. 5 presents a schematic diagram of a basic CAES system. Firstly, it consists of a motor (for charging) and a generator (for discharging). Furthermore, there is an air compressor with an air cooler for economic compression and reduction of moisture content of the compressed air. Next, there is a recuperator (to preheat the air from cavern) and a low and a high-pressure turbine. The container for storing compressed air is located underground, as mentioned above. Finally, there are equipment controls and auxiliaries, i.e., fuel storage and heat exchanger units [4,16]. Although the equipment used in CAES plants is mature and well proven, CAES plants lack the maturity of some other EES systems.

Some benefits of this system are similar to PHS systems; high power capacity, long energy storage duration (> 1 year), relatively quick start up and high efficiency (70–80%). Additionally, it requires a significant low capital cost ($400–800/kW), it has approximately 40 years lifetime and it creates little surface environmental problems due to the underground storage. Also, the self-discharge rate of the system is very low

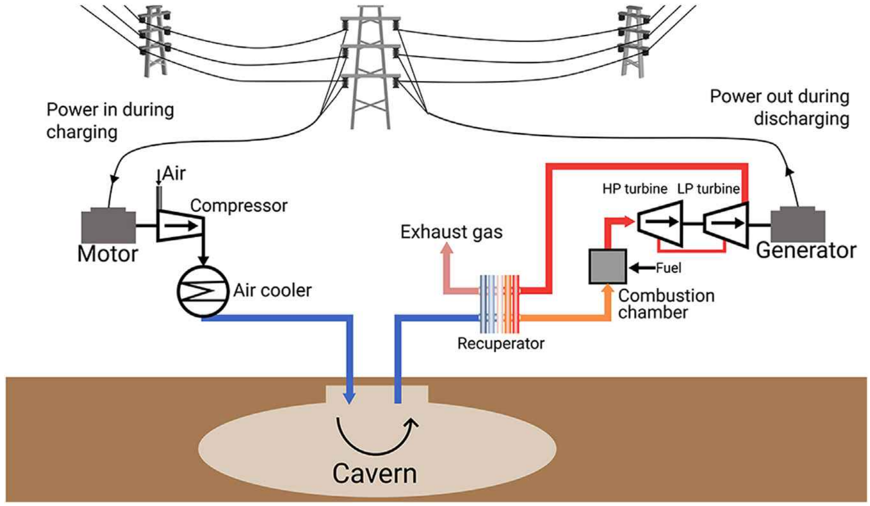

Fig. 5. A typical diagram of a CAES system.

(0.5%/day). On the other hand, CAES systems have low energy density (12 kWh/m^3) [18,19,27].

An improvement of CAES technology has been proposed over the last years, attracting research attention. The Advanced Adiabatic CAES (AA-CAES) is operated at the expansion mode, by integrating thermal storage. The stored energy in the cavern is converted into electrical energy with no need of a combustion process. In other words, the heat created from compression process is stored and used to reheat the air during expansion. Thus, the overall efficiency of the system is higher than the conventional CAES and fuel consumption is eliminated. An AA-CAES system is considered a promising technology because of its higher efficiency, the environmental friendliness and its reduced costs [7,23,28]. The first AA-CAES plant was built in 2016 in the Swiss Alps near the city of Biasca with a 500 kW capacity and autonomy of 4 h. An unused tunnel is used as the air storage cavern and a packed bed of rocks is used for thermal storage, placed inside the pressure cavern. The overall efficiency of the plant is estimated at about 63–74% [8,29].

2.3. Batteries

Batteries are the most popular and mature energy storage devices. They are classified as long-term energy storage devices. They can connect in series and/or parallel combination to increase their power capacity to be compatible with different applications. There are two main categories of batteries: electrochemical and redox flow batteries. Electrochemical batteries can store energy by creating electrically charged ions using chemical reactions between positive and negative plates. In other words, during charging the electricity (direct current) is converted to chemical energy, and during discharging the chemical energy is converted back to electricity (flow of electrons in direct current form) [30].

2.3.1. Lead-acid batteries

Lead-acid batteries are the most mature (invented in 1859) and widely used rechargeable electrochemical devices in vehicles and in stationary equipment. The anode is made of metallic lead (Pb), the cathode is made of lead dioxide (PbO_2) and the electrolyte is sulfuric acid (H_2SO_4) (Fig. 6). The chemical reactions at the anode and cathode of lead-acid battery are:

Anode: $$Pb + SO_4^{2-} \rightleftharpoons PbSO_4 + 2e^-$$

Cathode: $$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightleftharpoons PbSO_4 + 2H_2O$$

The rated voltage of a lead-acid cell is 2V and its lifetime is between 3 and 12 years [31]. Lead-acid batteries are low cost devices

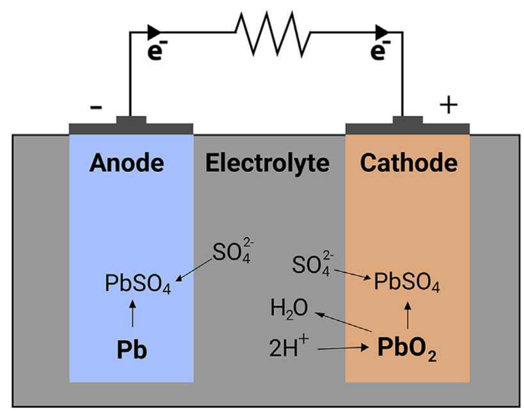

Fig. 6. Lead–acid battery storage with chemical reactions during discharge.

($150–500/kWh), have relatively high efficiency (65–80%) and are reliable and suitable for power quality and spinning reserve applications. Furthermore, their response time is fast (< 5 ms) and they have small daily self-discharge rate (< 0.3%/day). Among their disadvantages are the low energy density (25–45 Wh/kg), the low specific power (180–200 W/kg), the limited cycle life (200–1800 cycles), the high maintenance requirements and some environmental impacts (they emit explosive gas and acid fumes). Also, they are slow to charge and they have poor low temperature performance, so they require a thermal management system. It is not recommended to completely discharge the lead-acid batteries (because their lifetime depends on the cycle Depth-of-Discharge), so it is necessary to install a larger battery bank to keep the battery life constant. Furthermore, lead-acid batteries are expensive devices for RES because of their maintenance and replacement costs [4,16,18,25,32].

Cho et al. [33] presented an advanced lead-acid system with a split design for the negative electrode, known as ultra-battery, as demonstrated in Fig. 7. This system uses a Pb electrode connected in parallel with a modified carbon electrode as the negative electrode, with one PbO_2 electrode as the positive electrode [34]. This new configuration provides a high capacity and significantly longer cycle life (17,000 cycles) compared to the traditional lead-acid battery. The capital cost for the ultra-battery system is higher than the typical lead-acid battery, but it is possible to reduce the cost by increasing the scale of production [33]. In 2012 at the island of Maui, Hawaii, a 10 MW advanced lead-acid system was operated to support grid needs and provide ramp control and frequency regulation [8].

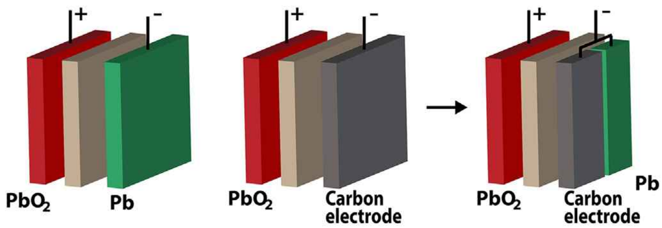

Fig. 7. Schematic of the advanced lead-acid battery (ultra-battery).

2.3.2. Nickel-based batteries

Nickel cadmium (NiCd) batteries are also mature devices since they have been used commercially since 1915. They use nickel hydroxide and metallic cadmium as the two electrodes and an aqueous alkaline solution as the electrolyte [31]. The following formulas describe the chemical reactions at the anode and cathode of NiCd battery:

Anode: $Cd + 2OH^- \rightleftharpoons Cd(OH)_2 + 2e^-$
Cathode: $2NiOOH + 2H_2O + 2e^- \rightleftharpoons 2Ni(OH)_2 + 2OH^-$

They are reliable and do not require high maintenance cost. They are the only batteries capable of performing well even at low temperatures (from –20 to − 40 °C). Their advantages are their high energy density (50–75 Wh/kg) and their long cycle life (2000–2500 cycles). Some barriers of the NiCd type are the toxic heavy metals (cadmium and nickel) used and the environmental harm they cause [35]. Moreover, their lifetime and maximum capacity decrease dramatically if the battery is repeatedly recharged after being partially discharged (memory effect). The cost of NiCd batteries is relatively high ($800–1500/kWh), their unit voltage is about 1.0–1.3 V and their energy efficiency is between 60% and 70%. Nickel cadmium batteries are not heavily used commercially and it seems that they will not be used for future large-scale energy storage applications [15,18,27,32]. NiCd batteries have been prohibited for consumer use within the EU since 2006 and are used only for stationary applications [36].

Nickel-metal hydride (NiMH) batteries are similar to the NiCd batteries except that the material used for electrodes is a hydrogen-absorbing alloy instead of cadmium (Fig. 8) [37]. The chemical reactions at the anode and cathode for the NiMH battery are:

Anode: $H_2O + M + e^- \rightleftharpoons OH^- + MH$
Cathode: $Ni(OH)_2 + OH^- \rightleftharpoons NiO(OH) + H_2O + e^-$

They first appeared commercially around 1995 to replace NiCd batteries. Their specific energy is moderate (70–80 Wh/kg) but their energy density is high (170–420 Wh/L). Additionally, they do not get affected so much from the memory effect and they are more environmentally benign than NiCd batteries. However, NiMH batteries have a low energy efficiency (65–70%) [16,18,32,36].

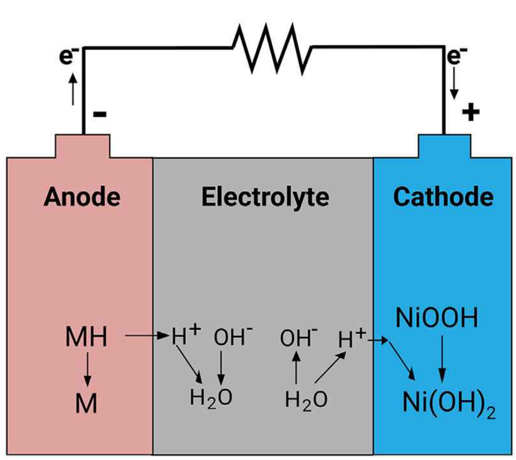

Fig. 8. NiMH battery storage reaction diagram during discharge.

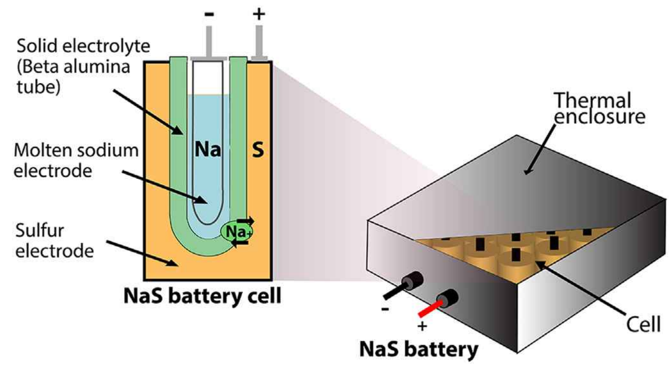

Fig. 9. Schematic of a NaS battery.

2.3.3. Sodium Sulfur (NaS) batteries

Sodium Sulfur (NaS) batteries were introduced in the 1960s. They are considered as one of the most promising solutions for large-scale stationary EES applications. Some of their applications include load leveling, power quality, peak shaving and renewable energy management and integration. The NaS battery system is constructed in a tubular design (Fig. 9). The anode is made of sodium (Na), the cathode is made of sulfur (S) and the solid electrolyte is made from beta alumina [12]:

Anode: $2Na \rightleftharpoons 2Na^+ + 2e^-$
Cathode: $S + 2e^- \rightleftharpoons S^{2-}$

The cell reactions normally require a temperature of 300–350 °C to ensure that the electrodes (Na and S) are in liquid state, leading to a high reactivity. At 350 °C the NaS battery exhibits a voltage of 2.07 V until 60–75% of the discharge process. After that, the voltage starts to decrease linearly to 1.78 V at the end of the discharge. The lifetime of a NaS battery is about 10–15 years. The desirable features of NaS batteries include relatively high energy density (150–240 Wh/kg), high power density (150–240 W/kg) and high rated capacity (up to 244.8 MWh). In addition, they have low maintenance needs, high energy efficiency (75–90%), long cycle life (2500–4500 cycles) and very fast response time (< 5 ms). The battery also uses inexpensive, non-toxic materials with high recyclability (about 99% recyclable). However, NaS batteries have some limitations regarding the high annual operating cost ($80/kW/year), the high initial capital cost ($300–500/kWh or $1000–3000/kW) and some safety problems (if both electrodes come into direct contact at high temperature, fires and explosions occur). In addition to that, a need of an extra system is required to ensure its operating temperature and sodium corrosion problem. The research and development focuses mainly on enhancing the cell performance indices and decreasing or eliminating the high temperature operating constrains [16,18,19,32,33,38,39].

2.3.4. Sodium nickel chloride (NaNiCl) batteries

The sodium nickel chloride (NaNiCl) battery (also known as ZEBRA battery) is similar to the sodium sulfur (NaS) battery. It is commercially available since 1995 and was intended to solve some development issues that NaS battery was experiencing at the time. It uses nickel chloride ($NiCl_2$) as the positive electrode, liquid sodium as the negative electrode and ceramic electrolyte to separate the electrodes:

Anode: $2Na \rightleftharpoons 2Na^+ + 2e^-$
Cathode: $NiCl_2 + 2e^- \rightleftharpoons Ni + 2Cl^-$

A sodium nickel chloride battery is a high temperature system (250–350 °C) with higher cell voltage (2.58 V) than a NaS battery. Among the advantages of such batteries are their better safety characteristics, their less corrosive properties, their good pulse power

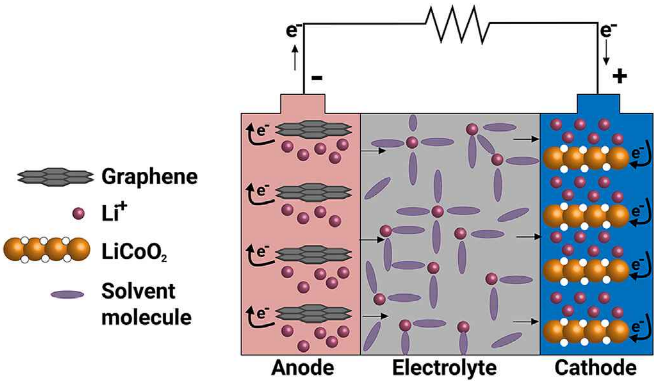

Fig. 10. Schematic of a lithium-ion battery.

capability, the fact that they are cell maintenance free and very low self-discharge, and their relatively high cycle life. Their limitations with respect to NaS batteries are their low energy density (100–120 Wh/kg) and their low power density (150–200 W/kg). Sodium nickel chloride batteries tend to develop low resistance when faults occur and this is why cell faults in serial connections only result in the loss of the voltage from one cell, instead of a premature failure of the complete system. They have been successfully implemented almost exclusively for electric vehicle applications. The related research nowadays focuses on hybrid electric vehicles and on storing renewable energy for load leveling and industrial applications. However, very few companies have been involved in the development of this technology and produce this type of battery, therefore its potential is limited [4,32,36,38,39].

2.3.5. Lithium-ion (Li-ion) batteries

Lithium-ion (Li-ion) batteries were commercialized by Sony in 1991. The cathode is composed of lithium-based compounds (e.g. $LiCoO_2$, $LiMnO_2$, $LiFePO_4$) and the anode is made from graphitic carbon (C). The electrolyte is normally a non-aqueous liquid organic solvent mix with dissolved lithium salts (Fig. 10). The chemical reactions of the Li-ion battery with lithium cobalt oxide cathode ($LiCoO_2$) are:

Anode: $LiC_6 \rightleftharpoons Li^+ + e^- + 6C$

Cathode: $CoO_2 + Li^+ + e^- \rightleftharpoons LiCoO_2$

Lithium ion cells have a nominal voltage of around 3.7 V. At present, lithium battery technology has achieved significant penetration into the portable consumer electronics and especially in laptop and mobile systems [40,41]. Furthermore, it is making the transition into hybrid and electric vehicle applications and has opportunities in grid storage as well [42].

The recent related research on Li-ion batteries focuses on cost reduction (which is about $600–2500/kWh) by the use of cheaper materials, lifetime increase and reduction of high flammability risk. Their advantages compared with NiCd and lead-acid batteries are the higher energy density (80–200 Wh/kg) and energy efficiency (90–97%), the lower self-discharge rate (< 5%/month) and the extremely low maintenance required. In addition, lithium ion batteries have fast response time (< 5 ms), high power density (500–2000 W/kg), wide operating temperatures (–20 to 60 °C for charge and –40 to 65 °C for discharge) and more than 1000–10,000 life cycles. Unfortunately, the lifetime of lithium ion batteries is temperature dependent and for that reason they are unsuitable for back-up applications where they may become completely discharged. Another drawback is the safety issue due to the metal oxide electrodes, which are thermally unstable and can decompose at raised temperatures, releasing oxygen and thermal energy. Therefore, to minimize this safety problem, lithium ion batteries are equipped with a monitoring unit to avoid over-charging and over-discharging. Furthermore, there is a maximum charge and discharge current limit on most packs [4,16,32,33,36,39].

There are several material combinations and various types of lithium-based batteries [43]. During the last few years, graphene has been considered as a promising material that will change dramatically the li-ion battery field and bring a huge improvement in their performance. It is flexible, almost transparent, environmentally friendly, lightweight and the most impermeable and strongest material ever tested. Also it has excellent thermal conductivity (3000 W/m/K) and high theoretical specific surface area (2630 m^2/g) [7,38,44]. Adding graphene at a lithium-ion battery's anode improves the battery's performance and increases its energy density and cycle life [45]. Moreover, incorporating hybrid materials with graphene at the cathode can enhance several characteristics of the battery. Specifically, graphene can be combined with Vanadium Oxide at the lithium-ion cathode to achieve fast charge and discharge characteristics. Furthermore, enhancing a lithium iron phosphate ($LiFePO_4$) cathode with graphene can increase the battery's storage capacity, improve the charging time and decrease its weight [46,47]. An increased attention on the integration of graphene has been paid by electric vehicles companies, but there is no any official announcement by the companies until today [48,49]. Graphene is also an attractive material for electronics companies. On November 2017, a team of researchers at the Samsung Advanced Institute of Technology developed the "graphene ball" [50]. This invention provides improved cycle life, increased capacity and fast charging capability (five times faster charging speeds than standard lithium-ion batteries). However, there is no commercial large-scale production so far. R&D is intensive, and the future of graphene-based batteries is definitely huge.

2.3.6. Metal-air batteries

Metal-air battery can be categorized as a special type of fuel cell using metal instead of fuel and air as the oxidant. A metal-air battery consists of the anode made of metal (e.g. lithium, aluminium, or zinc) and the cathode from porous carbon structure connected to an air supply, as seen from Fig. 11. The electrolyte is often a good OH-ion (metal-ion) conductor and it can be in a liquid form or a solid polymer membrane. The reaction is electrochemical and only oxygen is needed from air [4,33]:

Anode: $Zn + 2OH^- \rightleftharpoons Zn(OH)_2 + 2e^-$

Cathode: $H_2O + ½O_2 + 2e^- \rightleftharpoons 2OH^-$

There are various metal air battery chemical couples. One of them is the lithium-air battery, which has a theoretical specific energy of 11,140 Wh/kg, however the high reactivity of lithium with air and humidity can cause fire. At present, only zinc-air (Zn-air) batteries are technically feasible with an energy density near 470–650 Wh/kg. Metal-air technology offers high energy density, reasonable cost levels and it is environmentally friendly. However, the electrical recharging is difficult and inefficient (50% efficiency) with a life of a few hundred cycles and a limited operating temperature range (0–50 °C). Although rechargeable metal-air batteries are still under development, there are

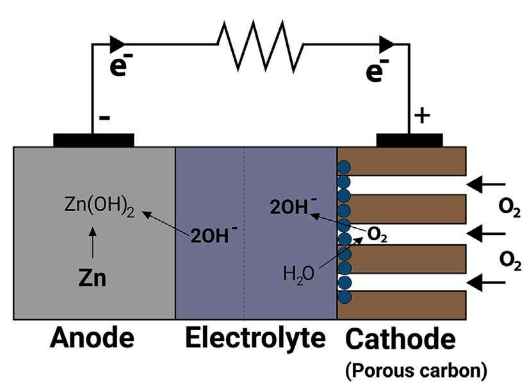

Fig. 11. Metal-air (Zn-air) battery storage during discharge.

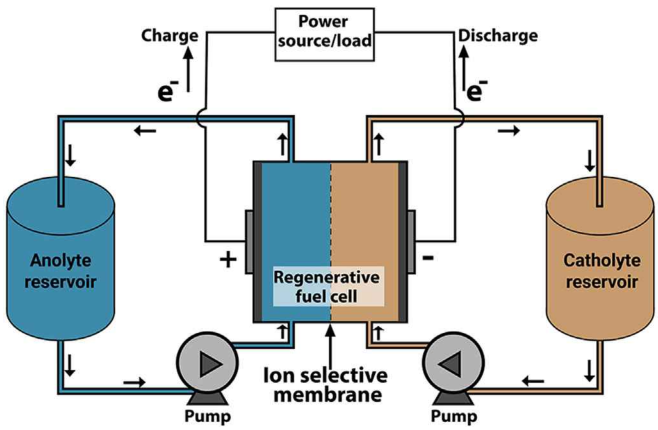

Fig. 12. Schematic of a flow battery.

some developers producing them [4,16,33,36].

2.3.7. Flow batteries

Flow batteries are relatively new and promising storage systems and are considered as long-term energy storage devices for large-scale applications. They convert electrical energy into chemical potential energy by charging two liquid electrolyte solutions and releasing the stored energy. The electrolytes are stored externally in tanks/reservoirs and pumped through the electrochemical cell that converts chemical energy directly to electricity and vice versa (Fig. 12). It is very easy to replace or increase the amount of the electrolytes, thus their capacity is easily scalable. Flow batteries have two sets of electrolytes which are pumped through separate loops and are separated by a microporous separator or an ion conducting membrane. The operation is based on reduction-oxidation reactions of electrolytes. During charging, the one electrolyte is oxidized at the anode and the other electrolyte is reduced at the cathode. During discharging, a reverse process occurs. Flow batteries can be used in a wide range of stationary applications. They overcome the disadvantages of typical electrochemical batteries, in which the electrochemical reactions create solid compounds that are stored directly on the electrodes causing limited storage capacity [32,51,52].

Redox flow technology offers significant benefits such as no self-discharge rate, no degradation for deep discharge, long lifetime and low maintenance requirements. On the negative end, it requires high investment cost and it has technical development issues. Redox flow battery is an attractive technology for large-scale EES systems (10 kW–10 MW) considering all the above benefits. Many researchers and manufacturers are offering flow batteries for stationary applications because of their positive characteristics regarding the self-discharge rate, the energy costs, the cycle life and the response time. However, further effort must be made to improve their performance and efficiency [4,53]. Some types of flow batteries that have been developed over the past few years are the vanadium redox flow batteries (VRB), the polysulfide bromide batteries (PSB), and the zinc-bromine batteries (ZBR).

2.3.7.1. Vanadium redox batteries (VRB). VRB is the most studied and mature type of flow batteries. The cell voltage is about 1.4–1.6 V. All chemical reactions are based on the transfer of electrons between vanadium ions in different oxidation states. Specifically, at the negative electrode V^{3+} is converted to V^{2+} during charging and during discharging V^{2+} ions are reconverted back to V^{3+} ions. A similar reaction happens at the positive electrode. During charging and discharging, H^{+} ions are exchanged between the two electrolyte reservoirs through the ion conductive membrane [32,34,54]. The chemical reactions are expressed by:

Anode: $V^{4+} \rightleftharpoons V^{5+} + e^{-}$

Cathode: $V^{3+} + e^{-} \rightleftharpoons V^{2+}$

Among all these types of flow batteries, vanadium redox batteries have some attractive benefits, such as better efficiency (75–85%), longer cycle life (12,000–14,000 cycles), better safety and lower operating cost and maintenance. Also, they do not get affected by deep discharges or if are left completely discharged for a long period. VRB are suitable for various applications, most of them are focused on stationary applications because they require large amount of space due to their low energy density (10–50 Wh/Kg). For instance, they can be used for power quality, load leveling applications and UPS devices. VRB have been installed and tested in various locations for different applications [28,33]. Uhrig et al. [55] states that for large capacities VRB can be competitive candidates compared to lithium-ion batteries regarding the economical viability. According to the Department of Energy (DOE) database [8], the larger power plant of VRB is located at Minamihayakita Transformer Station in Abira-Chou, Hokkaido, Japan. The power capacity of the plant is 15 MW and can provide power for 4 h. Finally, in 2016 the China National Energy Administration approved a VRB system of 200 MW capacity to be built in Dalian, China. It is estimated that it will be operated by the end of 2018 and will be the world's largest battery plant. The energy storage station will provide peak-shaving as well as grid stabilization [7,8]. Concluding, flow batteries and especially VRB are definitely the future technologies for stationary applications.

2.3.7.2. Zinc-bromine (ZBR) batteries. Zinc-bromine batteries are classified as a type of hybrid flow batteries. As shown in Fig. 12, one reservoir is used to store the electrolyte for the positive electrode reactions and the other one for the negative electrode reactions. Both electrolytes are aqueous solutions of zinc-bromide ($ZnBr_2$). During charge cycle, zinc is plated from electrolyte solution to negative electrode surface. At the positive electrode surface, bromide is converted to bromine and it is stored in the electrolyte tank. Therefore, zinc is electroplated onto conductive electrodes, while bromine is formed. During the discharge cycle, zinc dissolves in the electrolyte, thus a reverse process occurs [32,34,56]. The chemical reactions at the anode and cathode are described by:

Anode: $2Br^{-} \rightleftharpoons Br_2 + 2e^{-}$

Cathode: $Zn^{2+} + 2e^{-} \rightleftharpoons Zn$

ZBR batteries have similar features with VRB. However, ZBR batteries have relatively higher energy density (30–85 Wh/Kg) compared to VRB. Their cell voltage is about 1.8 V with discharge duration of up to 10 h. Additionally, they are applicable for seasonal storage due to the low self-discharge rate and the allowance to keep the battery fully discharged (100% DoD) without any damage [4]. According to DOE database [8], the larger power plant of ZBR batteries is located in Astana, Kazakhstan with a rated power of 25 MW and energy capacity of 100MWh. The system is estimated to have 20 years lifetime and can withstand 15000 charge and discharge cycles. The rest of the ZBR battery operational power plants are limited in the range of 10 kW–1 MW [8].

2.3.7.3. Polysulfide Bromide batteries (PSB). PSB batteries are based on the electrochemical reactions between two salt-based electrolytes; sodium bromide (for the positive electrode) and sodium polysulfide (for the negative electrode). The cell voltage is about 1.5 V. The polymer membrane separates the two electrolytes and allows only the interchange of positive sodium ions. During the charge process, bromide ions (Br^{-}) are transformed into tribromide ions (Br_3^{-}) at the positive electrode, while dissolved sodium particles (S_4^{2-}) are reduced to sulfide ions (S_2^{2-}). During discharging, a reverse process occurs [32,53]. The chemical reactions at the anode and cathode are expressed by:

Anode: $3Br^- \rightleftharpoons Br_3^- + 2e^-$

Cathode: $2S_2^{2-} \rightleftharpoons S_4^- + 2e^-$

This type of flow battery has relatively low efficiency of about 60–75% because of the pumping requirements. Also, in a case of a reservoir failure, toxic bromine gas is rejected leading to a negative environmental impact. PSB batteries are suitable for voltage and frequency regulation applications because of their fast response time [28,34]. Currently, there does not exist any large-scale plant of PSB batteries [8]. Regenesys Technologies had tried to build a PSB battery plant in a station in the UK of 15 MW power capacity. However, due to several financial and engineering constraints the plant remained uncompleted [32].

2.4. Hydrogen energy storage - Fuel cells

A fuel cell is an electrochemical cell that converts a fuel (chemical energy) into electricity. The cell consists of two electrodes on both sides of an electrolyte (Fig. 13). When the fuel (e.g. hydrogen) is fed to the anode and an oxidant (air or oxygen) is fed to the cathode, then a potential difference occurs between the two electrodes. The chemical equation is given by: $2H_2 + O_2 \rightarrow 2H_2O + \text{energy} + \text{heat}$, where electrical and heat energy are released during the process. Most of the cell types can perform the reverse process (regenerative or reversible fuel cell). The reversible fuel cell combines the functions of an electrolyzer and a fuel cell into one device. When a current is applied, the device acts as an electrolyzer producing hydrogen and oxygen from water. When applying a load, the device behaves as a fuel cell and generates electricity from hydrogen. In other words, when electricity is needed, the stored hydrogen can be used to feed the fuel cell [22]. That is, during off-peak hours electrolysis produces hydrogen, which can be stored to generate electricity during peak hours.

Hydrogen fuel cells can be characterized as long-term storage devices. Some of their benefits include high energy density (300–1200 Wh/kg), modular design, low maintenance needs, low toxic emissions, low noise and vibrations, almost zero daily parasitic loss, easy installation and low maintenance cost. Moreover, they can be transportable, highly versatile, compatible with a lot of types of fuels and suitable for small and large-scale applications. Hydrogen fuel cells have about 15 years lifetime with more than 20,000 charge and discharge cycles respectively. However, hydrogen fuel cells remain a very expensive method of storage ($2–15/kWh) and suffer from high storage cost ($500–10,000/kW) and low efficiency (20–50%). Cost reduction and durability improvement are essential to deploy hydrogen energy storage in large-scale applications [4,15,18,19,32].

At present, there are four main types of technologies of hydrogen storage, two of which are more mature and developed:

- The pressurized hydrogen method that depends on high materials permeability to hydrogen and their stability under pressure (200–350 bar).
- The second type of technology is based on the use of metal hydrides as storage mediums that relies on the excellent hydrogen absorption properties of these compounds. These compounds are capable of absorbing the hydrogen and restoring it when required. They have low equilibrium pressure at room temperature. This type of technology is safe for use at low pressure and it is compact because of the high-volume absorption capacities of the hydrides. However, a thermal management system is required because the absorption of hydrogen is an exothermic reaction, while desorption of hydrogen is endothermic [16,19].
- The liquid hydrogen storage, which is limited at present. This is due to its properties, the cost of the materials that are used in the manufacturing of the tank and the very low temperature that is required (–253 °C) [57]. Among the drawbacks of this method are the leaks from the unavoidable thermal losses, which lead to pressure increase inside the tank and the self-discharge of the tank that reach 3%/day or 100%/month.
- The fourth type is based on the use of carbon nanofibers, and is currently under research. However, there are many types of materials that are in the research stage depending on the temperature or the pressure of the hydrogen [16,19].

2.5. Thermal energy storage (TES)

Thermal Energy Storage (TES) systems can store heat using different means in insulated repositories for later use in many industrial and residential applications, like space heating or cooling, hot water production or electricity generation. TES can be simply defined as the temporary storage of thermal energy at low or high temperatures. Thermal storage systems are deployed for the overcoming of the mismatch between demand and supply of thermal energy and thus they are important for the integration of RES. A typical TES system consists of a storage medium in a tank, a chiller or a built-up refrigeration system, piping, pumps and controls [19].

TES technology can be divided into two categories based on the temperature level of stored thermal energy: the low temperature TES and the high temperature TES.

Low temperature TES is developed for commercial and industrial buildings for heating, cooling and water boiling. The low temperature TES technologies that are currently being used are the following:

(i) *Aquiferous low temperature TES*, where water is cooled or iced by a refrigerator during off-peak hours and stored for later use during peak hours. The amount of stored cooling energy depends on the temperature difference between the chilled/iced water stored in the tank and the returning warm water from the heat exchanger. This technology is applicable for peak shaving commercial and industrial cooling loads during daytime [4].

(ii) *Cryogenic energy storage (CES)*, where cryogen (e.g. liquid air or liquid nitrogen) is generated by off-peak power from RES. When electricity is needed, heat from the environment boils the cryogen and using cryogenic heat engine, electricity is released. Meanwhile,

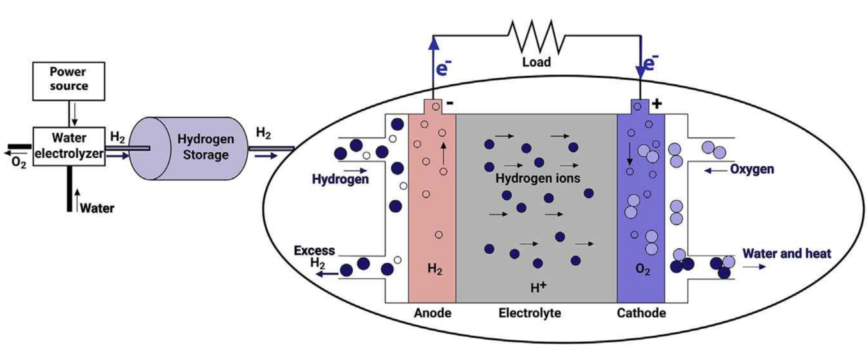

Fig. 13. Topology of fuel cell and hydrogen storage.

the wasted heat from the flue gas can be used to provide direct cooling and refrigeration. CES does not require significant capital cost per unit energy, is benign to the environment, it has high energy density (100–200 Wh/kg) and has long storage period. Apart from the benefits, CES has low efficiency (40–50%). CES is expected to be used for future grid power management [4,32].

High temperature TES is developed within solar thermal energy applications and plays vital role in renewable energy technologies and heat recovery. The high temperature TES technologies that are currently in use or are being under development are the following:

(i) *Concrete storage*. This type of technology uses concrete or castable ceramics to store energy at high temperatures for parabolic trough power plants. The heat transfer fluid can be a synthetic oil [4].

(ii) *Phase Change Materials (PCM)*. They are materials that can change phase, usually solid to liquid, at constant temperature. Latent heat is the energy exchanged during a phase transition, where there is no change of temperature during energy transfer. During accumulation, the bulk material shifts from solid to liquid and during discharge the liquid transfers back to solid. The heat transfer between the thermal collector and the environment are made through a heat transfer fluid (e.g. sodium hydroxide). This type of technology can be utilized for long-term seasonal storage. The advantage of latent heat storage is its capacity to store large amounts of energy in a small volume with a minimal temperature change as the change of phase is done at constant temperature, which allows efficient heat transfer [4,27,36,58].

(iii) *Molten salt storage and Room Temperature Ionic Liquids*. They are organic salts with negligible vapor pressure and a melting temperature below 25 °C. They can also be stored at high temperatures (many hundreds of degrees) without decomposing [4]. Concentrated Solar Power (CSP) systems use the sunlight to produce heat. The heat energy can be stored easily before conversion to electricity and eventually provide electrical energy by a conventional plant. CSP plants consist of two functionality parts: one that converts solar energy into heat and another that converts heat into electrical energy [24,59]. An example of a CSP plant is shown in Fig. 14. When there is sunlight, cold salt at about 265 °C is pumped from the cold temperature storage tank to the solar power tower. Hot salt at around 550 °C is generated by the concentrated solar beams at the receiver of the solar tower and then, it is used to produce steam in a steam turbine for electricity generation. Also, any additional hot salt is stored in a high temperature storage tank to be used during the night to generate additional electricity [60]. However, some CSP plants use molten salt as the heat transfer fluid in the solar collector. Instead of a power tower, they use parabolic troughs to focus sunlight onto a receiver pipe, through which the molten salt circulates [61,62].

The CSP has power capacity between 10 kW (for small applications) to 200 MW (for grid connection applications). When CSP plant is equipped with thermal storage this is considered as a long-term energy storage method because it can store energy for several hours. For example, they can produce electricity from heat even on cloudy days or after sunset. In other words, when production is required after sunset, the stored heat is released into the steam cycle and the plant continues to produce electricity. Additionally, the losses in thermal storage cycles of CSP systems are much less than other energy storage technologies (e.g. PHS, batteries). Thus, the thermal storage in CSP is more effective and less costly. The main disadvantages of CSP are the risk of the liquid salt to freeze at relatively low temperatures (265 °C) and the risk of salt decomposition at higher temperatures [24,59,63]. Kuravi et al. [64] listed several operational solar thermal power plants with integrated storage, including their characteristics regarding the type, storage medium, power plant capacity and storage duration capacity.

2.6. Superconducting magnetic energy storage (SMES)

Superconducting Magnetic Energy Storage (SMES) is a relatively new technology method that first induces DC current into a coil of a superconducting wire and then stores electrical energy in a magnetic field. There are no resistive losses nor any need for energy conversion to other forms [15]. When the wire reaches a temperature of −270 °C, the phenomenon of superconductivity occurs. As shown in Fig. 15, the main components of SMES are the superconducting unit, the refrigeration system and a power conversion system. The energy stored can be calculated as $E = LI^2/2$, where L is the inductance of the coil and I is the current passing through [4,65].

SMES is a short-term energy storage method with an extremely high operational cost ($1000–10,000/kWh) [66]. The response time is fast, which makes the SMES suitable for stability applications. Moreover, SMES is a reliable method and has high energy efficiency (90–95%). Also, the lifetime of the superconducting coil is high, although there is mechanical stress in the components leading to material fatigue [19,27].

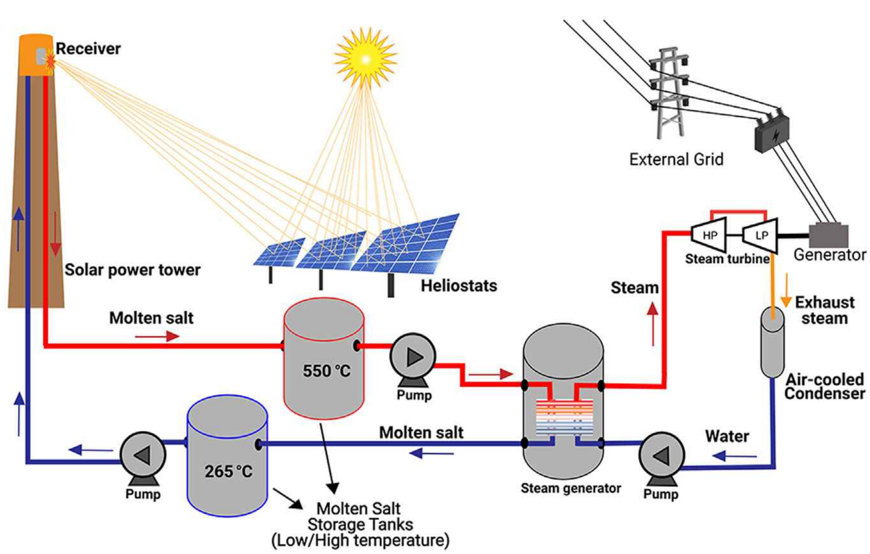

Fig. 14. CSP plant with thermal energy storage.

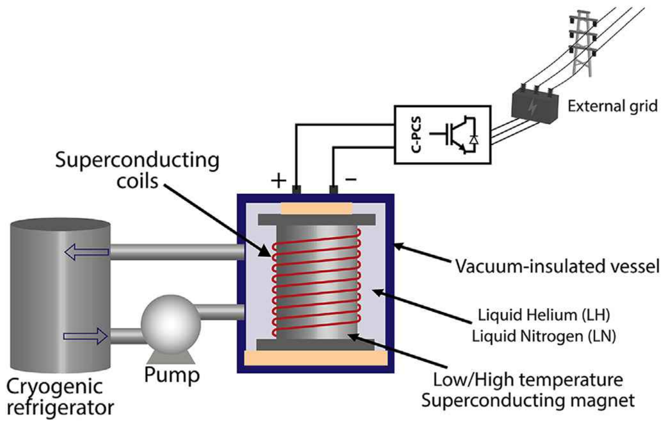

Fig. 15. SMES system.

2.7. Flywheel energy storage (FES)

The energy stored in a flywheel is in the form of kinetic energy of a rotating mass. It acts as a motor during charging, and as a generator from the rotational energy during discharging. The energy that can be stored is calculated as $E = J\omega^2/2$, where J is the moment of inertia and ω the angular velocity. The faster the flywheel rotates the more energy it stores [67]. Flywheel storage is considered as a short-term storage method, since the discharge time is from some minutes to 1 h [24,25]. There are two types of flywheel, the lower speed (up to 6000 rpm) and the higher speed (up to 60,000 rpm). Low speed flywheels have specific energy near 10–30 Wh/kg and they are made of steel rotors and conventional bearings. High speed flywheels can achieve specific energy of 100 Wh/kg because of the light weight and high strength composite rotors [15].

Fig. 16 shows the flywheel storage system, which consists of the motor/generator, the two magnetic bearings that rotate a mass in order to decrease friction at high speed and the vacuum to reduce wind shear. A flywheel storage device shares some attractive qualities such as long lifetime (15–20 years), long cycle life (10,000–100,000 cycles) and high efficiency (90–95%). However, flywheels have a high self-discharge (~20% per hour), so they do not constitute an adequate device for long-term energy storage. In addition to that, as mentioned above, the energy density is low and the capital cost is high [15,16,19,68].

Nowadays, the largest flywheel storage system is the EFDA JET Fusion Flywheel at Culham Science Centre, Oxfordshire, UK with total a power capacity of 400 MW. This power is available for 30 s, every

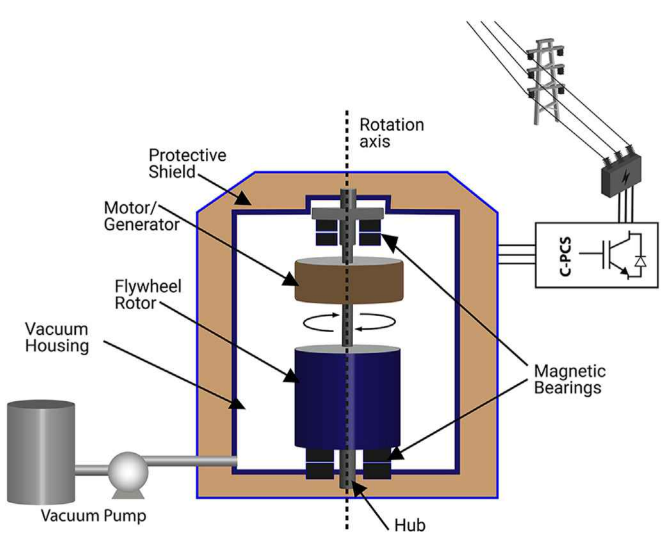

Fig. 16. The flywheel storage system.

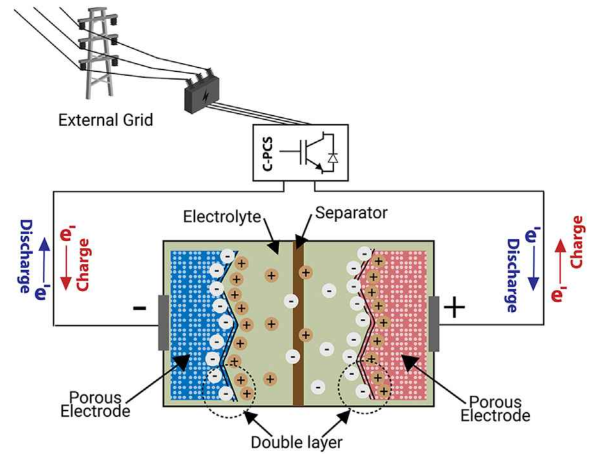

Fig. 17. Supercapacitor cell.

20–30 min for frequency regulation and on-site power generation [8].

2.8. Supercapacitors/Ultracapacitors

Supercapacitors, also known as electrochemical double layer capacitors or ultracapacitors, are relatively new energy storage devices. Energy storage is achieved with no chemical reaction, in the form of an electric field between two electrodes. The main difference between supercapacitors and conventional capacitors is that the supercapacitors have a very high energy density, because they have a larger electrode surface area coupled with a much thinner electrical layer between the electrode and the electrolyte. They both follow the same principle, except that supercapacitors have an electrolyte ionic conductor instead of an insulating material, in which ion movement is made along a conducting electrode with a large specific surface (Fig. 17) [16,27].

The electrodes are usually made of porous carbon or any other high surface area material. Recent technological progresses have allowed carbon aerogels and carbon nanotubes to be used as electrode material. The electrolyte is organic (which allows a nominal voltage of up to 3 V) or aqueous (whose nominal voltage is limited to 1 V). The function of the supercapacitor is simple; during charging, the electrically charged ions in the electrolyte are being moved towards the electrodes of opposite polarity due to the electric field between the charged electrodes [16]. Due to the low voltage resistance between the terminals of the supercapacitor, which is up to 3 V per element, supercapacitors are built up with modules of single cells connected in series or in a combination of series and parallel connections. The module voltage is typically 200–400 V. Single cells have a capacitance of 350–2700 F [15]. The energy stored in the supercapacitors can be calculated as $E = CV^2/2$, where C is the capacitance and V is the voltage across the cell or module [69].

Supercapacitors exhibit some favorable characteristics when compared with other energy storage devices. Firstly, they have high energy efficiency (85–98%), long life cycle (> 100,000 cycles), high power density (500–5000 W/kg) and very fast response time (< 5 ms). Moreover, they are environmentally friendly, as no thermal heat or hazardous substances are released during their discharge. Also, they have high tolerance to deep discharges and an extremely low internal resistance. Some of their drawbacks are the very short charge and discharge time (from some seconds up to some minutes), the low energy density (0.1–5 Wh/kg) and the high cost ($300–2000/kWh). Finally, their lifetime is up to 20 years and they have a high self-discharge rate (14% per month) [4,16,18].

An interesting project (Endesa STORE: La Palma Project) was constructed in 2013 in the Canary Islands to improve the reliability and operation of the grid. The supercapacitors are integrated in a conventional power plant and are able to respond to fast events (for up to 6 s) and to keep the frequency at an acceptable range. The same project also implemented two other plants of lithium-ion batteries (1 MW/ 3 MWh) and flywheels (0.5 MW/ 5 kWh) located also at the Canary islands [8].

3. Comparison of the various storage methods

The choice of the ideal storage method to be used depends on several factors: the amount of energy or power to be stored (small-scale or large-scale), the time for which this stored energy is required to be retained or to be released (short-term or long-term), spacing, portability, environmental issues, energy efficiency, cost, and so forth. For instance, PHS and CAES are used in stationary large-scale applications. Also, flywheels and supercapacitors are suitable for short-term applications, such as a brief auxiliary power supply due to an unexpected interruption. Further, CAES and flow batteries are a good choice for peak-hour load leveling when high energy storage is required (many MWh). Additionally, lithium-ion batteries are very efficient, but expensive for remote area applications. Although flow batteries are considered as a promising storage solution because they are scalable, they are still in the developing stage. Some other promising battery solutions are the lithium-ion batteries and NaS batteries. Table 1 and Table 2 contain the characteristics of all storage methods. A comparison of all energy storage technologies by their power rating, autonomy at rated power, energy and power density, lifetime in cycles and years, energy efficiency, maximum DoD (permitted), response time, capital cost, self-discharge rate and maturity is presented.

4. Grid scale energy storage applications

The widespread growth of the renewable energy technologies creates stabilization or quality problems to the grid. Moreover, when the wind is not blowing, or it is cloudy wind turbines and photovoltaic systems are not able to produce electricity respectively. The electric power system must keep in balance the real-time generation and load. Consequently, energy storage is required to provide smooth and uninterrupted electricity. EES technologies cover a wide spectrum of applications to the power network such as: (i) helping in meeting peak electrical demands, (ii) providing seasonal storage, (iii) regulating power, voltage and frequency, (iv) improving power quality and reliability, (v) supporting the smart grids, (vi) providing energy management, (vii) mitigating the fluctuations of renewable source power generation, (viii) reducing electrical energy import during peak hours and smoothing power demand, and (ix) providing standby power generation when a fault appears [71,99]. Case studies, performed by Hoff et al. [100], show that the addition of a storage for local load control and for emergency load protection are beneficial to the economics of customer-sited photovoltaic systems. Fig. 18 classifies the energy storage applications by the needs concerning energy, power and discharge time duration [101]. Most of the energy storage applications in the figure are explained in this section.

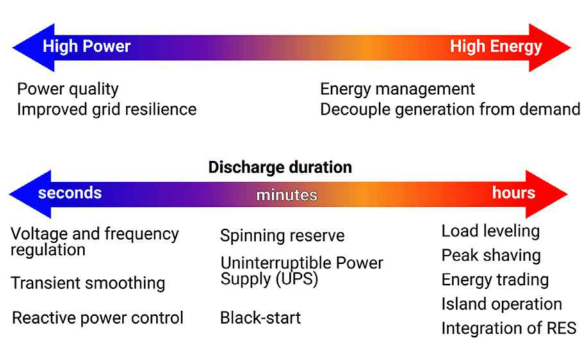

Fig. 18. Energy Storage Applications by the needs in energy, power and discharge time duration.

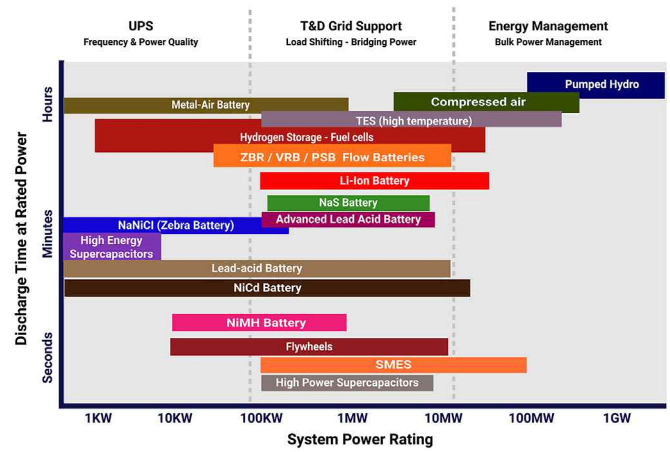

Fig. 19. Energy Storage Technologies by power capacity and discharge time.

Additionally, Fig. 19 summarizes all storage technologies by their power capacity and the duration for which this power can be relieved. The values for the power rating and the discharge time come from Table 1 and Table 2. This comparison is useful when considering which technologies are best for providing certain applications. For instance, Fig. 19 summarizes three application categories; (i) uninterruptable power supply (UPS), frequency and power quality, (ii) transmission and distribution (T&D) grid support and load shifting, and (iii) energy (bulk power) management [102]. Nourai [103] presented all storage methods and compared them with several characteristics. Also, Luo et al. [32] provided an overview of current and potential EES options for multiple applications.

- ***Power Quality***
  Power quality concerns the ability of the grid to supply a clean and stable power flow acting as a perfect power supply that is always available, with a pure noise-free sinusoidal wave shape, within voltage and frequency tolerances. The flow of reactive power and the presence of transients and harmonics in the network are the common contributors to voltage instability and interference on the voltage waveform. All these can affect the performance of some sensitive parts of equipment. Therefore, EES technologies can ensure a power quality improvement with a fast response time, high cyclability and a reasonable cost. Flywheels, supercapacitors and batteries contain all the above characteristics. Also, SMES may be a good choice [18,19,32,84]. Seo et al. [104] suggested supercapacitors for power quality control strategies in photovoltaic and wind turbine systems. Also, simulations confirm that supercapacitors can smooth the fluctuations caused by wind speed and irradiance variations.
- ***Frequency regulation***
  When the power consumption exceeds the generated power, due to increased customer usage or reduced generating capacity in the grid, the increased load on the generators will cause them to slow down and since the generators are synchronous machines, the grid frequency will also decrease. Similarly, if the consumption suddenly falls below the power generated or more generating capacity is switched into the network, the generator will speed up and the grid frequency will increase. Keeping the grid frequency and voltage within strict limits is essential for maintaining the stability of the grid. This requires access to very fast response means. A rapid drop of frequency may cause several problems, even a system collapse. Frequency support requires power to be delivered for a very short duration. The technologies that are capable for both regulation and power quality are the flywheels, SMES, batteries and supercapacitors. Supercapacitors have very fast response time, although their energy density is low. Delivering an instantaneous and

Table 1
Comparison of the various storage methods (except batteries).

Storage technology	Power rating (MW)	Discharge time at rated power	Specific energy (Wh/kg)	Specific power (W/kg)	Cycle life (cycles)	Lifetime (years)	Energy efficiency (%)	Maximum DoD (%)	Response time	Power capital cost ($/kW)	Energy capital cost ($/kWh)	Self-discharge rate (%/day)	Maturity
PHS	100–5000 [4]	hours–days [9]	0.5–1.5 [4]	–	10,000–30,000 [70]	30–60 [18]	65–85 [18]	95 [72]	min	500–4600 [74]	5–430 [9]	0.01 [7]	Mature
			1–2 [36]		50,000 [7]		80–100 [71]	100 [73]		700–2000 [75]			
CAES	5–300 [31]	hours–days [24]	30–60 [4]	–	8000–12,000 [4] 50,000 [7]	20–40 [4]	70 [19] 80 [25]	70 [72]	sec–min	400–800 [18]	40–80 [71] 50–150 [76]	0.5 [7]	Commercialized
Hydrogen fuel cell	0.001–50 [77]	minutes–hours [9]	300–1200 [78]	500 + [4]	20,000 + [32]	5–20 [70] 5–15 [4]	20–50 [4] 30–40 [18]	90 [72] 40–60 [71]	< 5 ms	500–10,000 [18]	2–15 [53]	Almost zero [4]	Developing
TES (high temperature)	0.1–300 [19]	hours [32]	80–200 [4]	10–30 [4]	–	5–40 [19] 5–15 [4]	30–60 [4] < 60 [24]	–	Not for rapid response	100–400 [32]	3–130 [79] 3500–7000 (CSP) [24]	0.05–1 [4]	Developed
SMES	0.1–10 [80] < 100 [9]	seconds–30 min [9]	0.5–5 [4]	500–2000 [4]	100,000+ [81]	20–30 [18]	90–95 [74]	100 [27]	5 ms	200–300 [4]	1000–10,000 [4]	10–15 [18]	Developing
Flywheel	0.01–10 [76]	seconds–minutes [37]	10–30 (low speed) [4]	400–1500 [28]	10,000–100,000 [18]	15–20 [18]	90–95 [18]	75 [71]	seconds	110–330 [77]	1000–5000 [32]	100 [16]	Developed
	0.1–20 [9]		100 (high speed)				70–95 [70]	100 [82]				55–100 [18]	
Supercapacitors	0.01–1 [83]	seconds–minutes [9]	0.1–5 [84]	800–2000 [27]	100,000 + [4]	10–20 [18]	85–98 [16]	75 [71]	< 5 ms	100–300 [4]	300–2000 [76]	0.5 [16]	Developing
			2.5–15 [4]	500–5000 [4]	500,000 [16]	20 + [4]						5 [27]	

consistent power supply can be an elusive goal. Yet without it, grid frequency regulation is impossible and frequency regulation remains one of the primary economic drivers for grid-scale storage today [18,19,32,84].

- ***Peak shaving***

  Peak shaving is the way of changing the pattern of energy supply so that the generation of energy for consumption during the hours of peak demand is shifted to off-peak periods. In other words, the energy is stored when there is excess in renewable energy production and it is released to the grid during periods of high demand (Fig. 20). The storage technology must be scalable and able to provide energy for some minutes to some hours. Currently, the most applicable technologies are PHS, CAES, electrochemical batteries, flow batteries and hydrogen fuel cells. Batteries are capable because of their fast response and the long duration of energy supply [18,19,32,84,105]. Senjyu et al. [106] proposed a model for leveling the power of photovoltaic array with battery storage, calculating the optimal size of the battery to minimize the capital cost. According to Toledo et al. [107] sodium sulfur (NaS) batteries are suitable for peak shaving applications in photovoltaic systems.

- ***Load leveling***

  Load leveling is the rescheduling of the loads to limit the requirements during periods of high demand and to increase the production of energy during off-peak periods for immediate storage and subsequent use during high demand periods (Fig. 21). The storage technology must be able to provide energy for some minutes to some hours. As for the case of peak shaving, the most applicable technologies are PHS, CAES, electrochemical batteries, flow batteries and hydrogen fuel cells [18,19,32,84,105].

- ***Load following***

  Energy storage can provide support in the following load changes of electricity demand. In other words, storage can act as an energy source or sink in response to both load and generating capacity changes. Most types of storage can also respond much more quickly than typical rotary generators when more or less output is needed for load following. Similarly, they can usually operate at partial output levels with relatively modest performance penalties. On the downside, storage systems cannot supply power indefinitely and the duration of supply is limited by the storage capacity [18,19,32,84].

- ***Seasonal storage***

  Seasonal storage requires high energy capacity and low self-discharge rates. Also, an advantage can be the efficiency and the power density. The selected storage technology for seasonal storage should be able to store energy for days to months, to compensate for a longer-term supply disruption or seasonal variability on the supply and demand sides of the energy system. For example, an underground TES system may store heat in the summer to use it in the winter. For this case, PHS, CAES, hydrogen fuel cells and flow batteries are more technically acceptable. However, PHS has low energy density and this may cause unacceptable changes to water levels. Also, hydrogen fuel cells have low efficiency and for this reason may be unsuitable [18,19,32,74,84].

- ***Integration of Renewable energies***

  The main problem with RES is that they are intermittent and thus they may be available when they are not needed and may not be available when they are needed. Unfortunately, the power output from these sources cannot be accurately predicted or controlled by grid operators. Thus, most renewable energy installations such a wind farms and solar arrays would better be utilized with the use of storage. For instance, Zahedi [108] proposed a solar photovoltaic combined with battery and supercapacitor. Depending on the application, renewable energy installations may use a variety of storage technologies [18,19,32,84].

- ***Emergency back-up power generation***

  In the case of a network failure, energy storage systems can act as emergency suppliers to provide adequate power until the system be

Table 2
Comparison of various battery storage technologies.

Battery storage technology	Power rating (MW)	Discharge time at rated power	Specific energy (Wh/kg)	Specific power (W/kg)	Cycle life (cycles)	Lifetime (years)	Energy efficiency (%)	Maximum DoD (%)	Response time	Power capital cost ($/kW)	Energy cost ($/kWh)	Self-discharge rate (%/day)	Maturity
Lead-acid Battery	0–20 [18]	seconds–hours [31]	25–45 [85]	180–200 [53] 75–300 [4]	200–1800 [32] 500–1000 [4]	3–12 [39] 5–15 [4]	65–80 [18] 75–85 [86]	60–70 [72]	< 5 ms	300–600 [18]	150–500 [76]	0.1–0.3 [18]	Mature
NiCd Battery	0–40 [32]	seconds–hours [31]	50–75 [18]	150–300 [4]	2000–2500 [18] 3500 + [19]	10–20 [4]	60–70 [86]	100 [42]	< 5 ms	500–1500 [87]	800–1500 [31] 400–2400 [53]	0.2–0.6 [4]	Mature
NiMH battery	0.01–1 [37]	Hours [37]	70 [88] 80 [16]	175 [88] 200–1500 [37]	< 1800 [16] 500 [88]	15 [88]	65–70 [16] 64 [89]	60–70 [42]	< 5 ms	600–1800 [37]	200–729 [79] 960–1800 [37]	0.4–1.2 [37]	Commercialized
NaS battery	0.15–10 [90]	seconds–hours [31]	85 [88] 150–240 [4]	150–240 [18] 115 [88]	2500–4500 [18]	10–15 [4]	75–90 [18]	90 [73]	< 5 ms	1000–3000 [90] 2000 [18]	300–500 [31]	0.05 [7]	Commercialized
NaNiCl(ZEBRA) Battery	0–0.3 [80]	seconds–hours [31]	100–120 [4]	150–200 [4]	2500 + [4]	10–14 [4]	90 [86]	75–85 [91] 80 [92]	< 5 ms	150–300 [4]	100–345 [79]	5 [7]	Commercialized
Lithium-ion Battery	0.1–50 [53]	minutes–hours [76]	80–150 [16] 75–200 [4]	500–2000 [16] 1800 [88]	~4500 [38] 1000–10,000 [93]	5–15 [4] 5–20 [93]	90–97 [32] 95–99 [93]	80 [42] 85–90 [73]	< 5 ms	1200–4000 [4]	600–2500 [80] 1200–4000 [94]	0.1–0.3 [4]	Commercialized
Metal-air (Zn-air) battery	0–1 [38]	seconds–24^{+} hours [31]	110–420 [84] 450–650 [95]	100 [80]	100–300 [4]	0.17–30 [79]	~50 [84] 60–65 [37]	90 [73]	< 5 ms	1750–1900 [96]	10–60 [4] 325–350 [38]	0.005–0.01 [79]	Developing
Vanadium Redox flow Battery (VRB)	0.3–15 [19]	seconds–10 h [4]	10–50 [97]	166 [32]	12,000–14,000 [98]	5–20 [7]	75–85 [18]	100 [71]	< 5 ms	600–1500 [90]	150–1000 [37] 600–1500 [94]	0.15 [7]	Developed
Zinc-bromine Flow battery (ZBR)	0.05–10 [32]	seconds–10 h [4]	75–85 [18] 30–50 [4]	100 [32] 45 [88]	2000 + [18] 10,000 [38]	5–20 [7]	75–80 [18] 60–65 [38]	100 [71]	< 5 ms	700–2500 [4] 400 [95]	340–1350 [38]	Almost zero [95]	Developed
Polysulfide Bromide battery (PSB)	0.1–15 [32]	seconds–10 h [4]	15–30 [32]	–	2000 [28]	10–15 [34]	60–75 [28]	100 [71]	20 ms [34]	700–2500 [4]	150–1000 [4]	Almost zero [32]	Developing

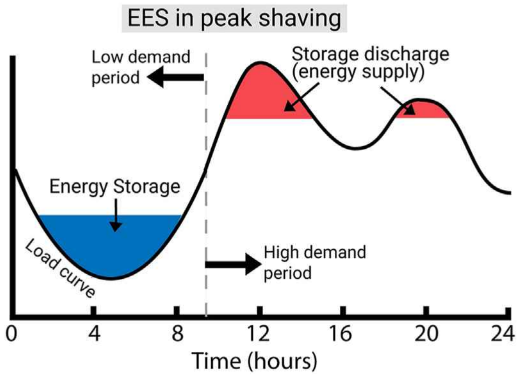

Fig. 20. Energy storage load profile in peak shaving.

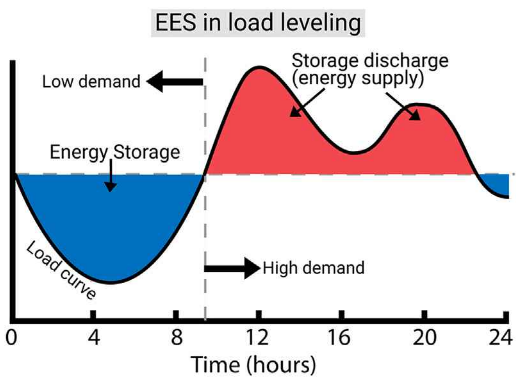

Fig. 21. Energy storage load profile in load leveling.

restored [14]. For this case, rapid response time storage technologies are needed with relatively long duration of discharge time. The most suitable technologies are batteries, flow batteries and flywheels [18,19,32,84]. Masaud et al. [24] state that CAES are able to provide backup electricity during long blackouts.

- ***Black-start***
  EES can provide a start-up from a shutdown condition to a system without taking power from the grid. This happens in case the system fails to provide energy therefore units are unable to restart [109]. This application requires a storage system with a fast response time, thus batteries and supercapacitors are suitable methods. An example of an installed EES is a CAES plant in Huntorf, Germany, providing black-start to nuclear units near the North Sea [32,80].
- ***Spinning reserve***
  In the case of a fast increase in generation or a fast decrease in load demand, energy storage systems can provide spinning reserve for the prevention of unexpected problems in the grid. In other words, spinning reserve is the unused capacity that can be activated by decision of the system operator and which is provided by devices that are synchronized to the grid and can affect the active power. Such systems must respond immediately, with the ability to maintain the output for some minutes up to a few hours. Some suitable storage methods are the flywheels, the batteries, the SMES and the flow batteries. Also, some other promising technologies are the CAES and PHS systems [76]. Spinning reserve is also helpful in isolated systems. Several studies examined the spinning reserve functionality using batteries and flow batteries in wind power plants [53].
- ***Uninterruptible Power Supply (UPS)***
  In the case of a power interruption or a power surge then EES must provide power to the system. UPS systems react immediately by providing energy for some minutes up to two hours. They are designed to automatically provide emergency power with no delay in case of an interruption or unacceptable situation of the grid supply. UPS is applicable in fire protection systems, security systems and in computers and servers, where the data must be protected. The most suitable technologies are batteries, flywheels and supercapacitors [32,101,110].

5. Hybrid energy storage

Hybrid energy storage refers to the integration of two or more different storage technologies into a system. This is achieved by combining the advantages and characteristics of different storage methods to achieve specific requirements and improve the whole system performance. The combination of energy and power rating, life cycle, duration of discharge period and other characteristics cannot be satisfied by the simple EES technology. Among all storage technologies, SMES, supercapacitors, flywheels and high power batteries have high power rate and short discharge duration. Contrarily, PHS, CAES, hydrogen fuel cells and high energy batteries have high energy rates and long duration of storage. It is necessary to choose an appropriate combination of energy storage systems to follow the system requirements [111–115]. Below a review of the current combinations of EES is presented.

- ***CAES-TES***
  The first large pilot power plant, ADELE, uses adiabatic CAES and TES technologies for better efficiency (about 70%), preventing fossil fuel consumption. It is planned to have a 1 GWh storage capacity and 200 MW of power generation with an autonomy of 5 h. The aim of the plant is the optimization and smooth interaction of the individual energy sources, especially of wind power. The project is designed to be built in Germany, but it is on hold due to non-technical reasons [8,116].
- ***CAES-Supercapacitor***
  Lemofouet and Rufer [117] presented a hybrid energy storage system using CAES and supercapacitors for maximum system efficiency. The CAES system provides energy and long storage periods while supercapacitors offer power smoothing. Additionally, Martinez et al. [118] proposed a similar hybrid system and provided the dynamic modeling and control algorithm of the system.
- ***CAES-Flywheel***
  Zhao et al. [119] studied the hybrid storage of an adiabatic CAES and the flywheel storage system for a wind power plant. The stochastic and intermitted nature of the wind leads to power fluctuations that can be eliminated through hybrid energy storage. The design and parametric analysis of the system is carried out to examine the effects of several parameters, such as the ambient conditions, inlet temperature of compressor, storage cavern temperature and maximum and minimum pressures of storage cavern.
- ***Fuel cell-SMES***
  Sander and Gehring [120] proposed the LIQHYSMES hybrid plant to solve several problems that are caused by the increased contribution of RES to the grid. The plant uses the high volumetric energy density of liquid hydrogen to provide long-term storage for large-scale stationary applications. Furthermore, the integration of SMES achieves short-term applications, such as load balancing. Another interesting back-up system for renewable generation was designed by researchers in Japan, combining a SMES system (cooled with liquid hydrogen) with a hydrogen fuel cell system [121].
- ***Fuel cell-Supercapacitor***
  There are many studies concerning the hybrid storage of hydrogen fuel cells and supercapacitors. Some researches focus on the application to electric vehicles while others examine the integration of RES. Thounthong et al. [122] proposed a control strategy of hybrid fuel cell-supercapacitors for electric vehicles. The polymer electrolyte membrane (PEM) fuel cell acts as the main power source and the supercapacitors as the auxiliary power source for electric vehicles. Furthermore, a hybrid PEM fuel cell-supercapacitor system

for stand-alone residential applications was examined by Uzunoglu and Alam [123]. Mathematical and dynamic electrical models were proposed and simulated. The combination of fuel cells and supercapacitors may increase the energy efficiency of the system, reduce the cost of fuel cell technology, and improve fuel usage. Apart from the above studies, there are various researches in the literature regarding the hybridization of fuel cells and supercapacitors for several control strategies [124,125] or for power and energy management applications [126,127].

- ***Fuel cell-Battery***
  The combination of fuel cell and battery is one of the most studied hybrid storage system. Many researchers propose the fuel cell-battery hybrid storage for RES integration (mostly by photovoltaics and wind turbines) and distributed generation [128]. Several types of batteries combined with fuel cells are depicted, namely lead-acid [129,130], lithium-ion [131] and flow batteries [132]. However, increased attention is also paid on automotive applications and on electric vehicles for powertrain performance improvements. For this case, lithium-ion batteries [133,134], lead-acid batteries [135] and sodium nickel chloride (ZEBRA) batteries [136] were studied.
- ***Battery-Flywheel***
  Flywheels provide high power for a short period of time with high efficiency and high cycle life. Briat et al. [137] examined the design and the integration of a flywheel storage system into an electric vehicle power train. They proposed a method to improve the system performance by keeping the battery power within rated levels for charges and discharges, while flywheel provides or recovers the energy during acceleration or braking, respectively. In addition, an application of battery-flywheel storage system for power stabilization on a large-scale wind farm was studied in [138]. The combination of battery and flywheel can also be applied on a UPS system [139] or on aerospace applications [140]. Moreover, a stand-alone house with RES and battery-flywheel storage system is depicted in [82], in which the authors proved the economic and technical feasibility of the system. Finally, Barelli et al. [141] provided a dynamic analysis of a hybrid battery-flywheel storage system coupled to a photovoltaic plant and a residential load. The authors considered the effect of components sizing, the power flow control management and the different weather conditions. As a result, this hybridization allowed load management, peak shaving, power quality improvement and enhanced life of the battery.
- ***Battery-SMES***
  The utilization of a battery and SMES technologies leads to various advantages, such as high efficiency, fast response time, high power and energy density and high cycle life. However, a SMES system requires the use of a refrigeration system that is an expensive solution. Therefore, the SMES is limited to some stationary applications like renewable power generation [142–144] and railway supply substations [145]. Specifically, Cansiz et al. [144] proposed a hybrid system using lithium-ion battery and SMES into an interconnected microgrid operation. The authors examined a case of a fault, in which the SMES responds immediately to maintain the voltage of the system, and battery is switched on when the fault remains and the SMES cannot supply enough power.
- ***Battery-Supercapacitor***
  There are many researchers who propose the use of batteries and supercapacitors together. This combination offers high storage capacity and a very fast response time [146]. Kanchev et al. [147] proposed an energy management method in a building with photovoltaic arrays and a hybrid storage. Specifically, excess energy from photovoltaics is stored in batteries and the local real-time power control is achieved by supercapacitors. Liu et al. [148] proposed a control strategy in a wind power system, using batteries and supercapacitors to relieve battery stress and extend the lifetime of the battery. Zhang et al. [149] presented an application of a battery-supercapacitor hybrid storage in a microgrid. Furthermore, some researchers proposed a hybrid system (battery-supercapacitor) for electric vehicles for better performance, higher efficiency and extended battery life [150–152]. Zhang et al. [153] indicated some control strategies using batteries and supercapacitor bank to provide transient power and peak load requirement. Finally, regarding the types of batteries used, Wang et al. [154] proposed flow batteries (VRB) for a 1 MW photovoltaic plant connected to the grid.

6. Conclusions

Energy storage is the key element for a new smart power world, based mostly on forms of renewable energy. Most of the energy storage technologies are technically developed and commercially available, but are not mature yet. Most of them are still an expensive solution and need more investigation on their durability and reliability.

In this paper, an up to date and comprehensive review of current energy storage technologies and their characteristics has been presented and analyzed. The review included storage properties and functionalities, advantages, disadvantages and their historical progress in the industry. Specifically, a comprehensive overview of Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), several types of batteries, Hydrogen Fuel Cells, Thermal Energy Storage (TES), Superconducting Magnetic Energy Storage (SMES), Flywheel Energy Storage (FES) and Supercapacitors has been presented. Furthermore, comparison tables of the most important characteristics of all storage methods have been given. All storage technologies can reinforce the quality, stability and reliability of the grid electricity systems. However, the proper storage method should be selected based on several parameters, such as the capital and operational cost, the power density, the energy density, the lifetime and cycle life and the efficiency. Also, capacity and portability should be considered. Finally, an extended discussion on hybrid energy storage combinations and applications has been performed. Hybrid energy storage can be integrated into various systems to achieve different applications. Hybrid storage has significant features and outstanding performance in some specific applications compared to single energy storage. These applications include transportation, renewable energy integration and grid support. More suitable hybridization for transport and electric (battery-powered) vehicles are the battery-supercapacitor and the battery-flywheel storage. Regarding the fuel cell-powered vehicles, the combinations of fuel cell-supercapacitor and fuel cell-battery are most applicable. For the case of renewable energy integration, there are several options of hybrid storage, such as battery-supercapacitor, battery-SMES, battery-flywheel, fuel cell-supercapacitor, fuel cell-SMES and fuel cell battery. Regarding the power smoothing and grid integration for photovoltaic and wind plants, the battery-supercapacitor and fuel cell-battery hybridization are considered to be the most suitable.

The selection of the system for a certain application depends on a variety of factors. Therefore, it can be suggested that the analysis presented in the current paper can be used to identify and compare the right storage system, before selecting the most appropriate option. Simulations of such modelled systems under real operating conditions will help toward this direction.

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