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Comparative Review of Energy Storage Systems, Their Roles, and Impacts on Future Power Systems

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ABSTRACT It is an exciting time for power systems as there are many ground-breaking changes happening simultaneously. There is a global consensus in increasing the share of renewable energy-based generation in the overall mix, transitioning to a more environmental-friendly transportation with electric vehicles as well as liberalizing the electricity markets, much to the distaste of traditional utility companies. All of these changes are against the status quo and introduce new paradigms in the way the power systems operate. The generation penetrates distribution networks, renewables introduce intermittency, and liberalized markets need more competitive operation with the existing assets. All of these challenges require using some sort of storage device to develop viable power system operation solutions. There are different types of storage systems with different costs, operation characteristics, and potential applications. Understanding these is vital for the future design of power systems whether it be for short-term transient operation or long-term generation planning. In this paper, the state-of-the-art storage systems and their characteristics are thoroughly reviewed along with the cutting edge research prototypes. Based on their architectures, capacities, and operation characteristics, the potential application fields are identified. Finally, the research fields that are related to energy storage systems are studied with their impacts on the future of power systems.

INDEX TERMS Storage systems, electric vehicles, power system optimization, market liberalization, renewable energy, new operation schemes, power system planning.

I. INTRODUCTION

In order to meet the carbon neutrality by energy sector in 2060 and to bind the temperature increases at 1.75° C by the year 2100 which is the midpoint of Paris Agreement's ambition, would require unprecedented policy action in development of optimal energy resources by minimizing the fuel consumption and toxic emissions causing greenhouse effect [1]. This requires outsized contribution from non-renewable energy resources in energy sector nearly 74% (including wind, solar, solar thermal, biogas, tidal and sustainable bioenergy with carbon capture and storage (CCS) technology) by placing the nuclear and fossil fuel based power plants with CCS technology at 15% and 7% energy production respectively and remnants from the natural gas fired generation [2]. With 2.1% global energy intensity improved in 2016, it is approximated that half of the global

energy growth demand of 2016 was supplied by renewables. Same year electric car sales placed a new record of 40% increase giving momentum to the transportation technology towards electric fuel based transport [3]. Fig. 1 illustrates that between 2017 and 2022, energy growth of 43% amounting to 920 GW is expected in the global renewable electricity capacity [4]. Thereby energy share of renewables will reach 30% in 2022, up from 24% in 2016 in which solar PV and solar thermal will rise faster than any other fuels. According to International Energy Agency (IEA) in next decade, renewables will represent the largest annual additions than any other fossil fuels [4].

However, the intermittent nature of the renewable energy resources and power fluctuations over multiple time horizons increases the complexity of grid planning and operation [5]. Which underpins the need for advanced energy storage

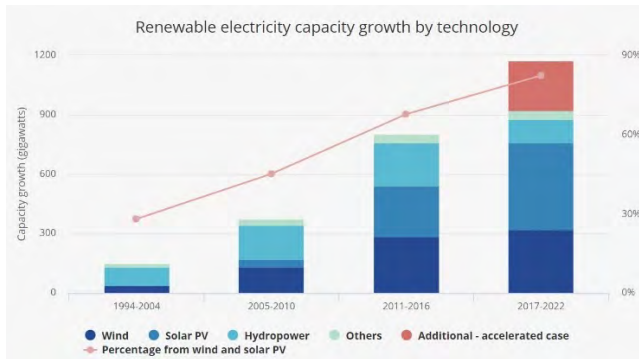


FIGURE 1. The capacity of Renewables entering in new era [4].

systems (ESS) technology with State-of-the-art system approach to endorse the renewable energy sector of new era. With ESS the intermittent production profile of renewables can be mapped to desirable supply profile [5]. ESS can absorb the energy when generation exceeds load and supply back to the grid during the peak load hours.

In smart grid architecture, microgrids are the promising component to be operated as controlled cell under grid connected and islanded mode [6], [7]. According to the flexible load characteristics of smart microgrid ESS should be scalable, autonomous and ready to cooperate with other grids to maintain the efficiency, providing containment of fluctuations in power and frequency for grid connected and islanded mode of operation [8], [9]. As shown in Fig. 2 the integration of ESS in grid connected and isolated scenarios have its unique merits ranging from power quality improvement to off grids services like microgrid stability and electric vehicles [10].

Having a mix of centralized and distributed power generation scenario in smart grid with significant part of overall usage supplied by decentralized generation, the major role of decentralized generation become dubious without effective and economic ESS technology [11], [12]. Large scale penetration of ESS provides the opportunity for demand-side management (DSM) and peak load demand shaving ultimately lowering the burden of new generation capacity to be installed [13], [14]. In stabilizing the grid with persistent power of ESS judicious design [15], accurate control techniques along with policy recommendations need to be in place for the safety of charging and discharging, energy conversion interface and fortification from dangers to the equipment in place [16], [17]. Electric vehicles (EV) complements grid storage capacity and acts as mobile electric storage besides limiting the CO₂ emissions and fossil fuel consumption [18], [19]. Plug-in electric vehicles (PEV) and smart electrical park may take smart grid to next level through participating in energy trading of DSM to reduce overall electric cost and peak-to-average ratio in real time pricing policy [20]–[22]. Dedicated R&D is needed to overcome the limitations of ESS in terms of driving range and cost of EVs as given in [23]. Optimal evaluation and selection of energy storage systems with respect to their application

and surrounding environment is significant in power system network. This review paper encapsulates the different ESS technologies, their classification and technical assessment based on characteristics and applications along with the challenges of automation and standardization of the ESS required in smart grid environment. Therefore, this review lay out the significant information for implementing the ESS and their integration in the future smart grid technology.

II. OVERVIEW OF ELECTRICAL ENERGY STORAGE TECHNOLOGIES

The storage of electrical energy will be done by transforming electrical energy into another form viz. mechanical, chemical, thermal, electrical or electrochemical [24]. As given in [5] the type of energy production, storage duration and end application will affect the features of ESS which are derived in theoretical framework as per (1).

$$ST(t) + PR(t) = SU(t) \tag{1}$$

where $ST(t)$ is the storage power of the ESS taken as function of time, it is considered to be positive when discharging the power and negative when charging. $PR(t)$ is power production profile by installed generation system, which is either supplied to ESS or to the grid or lost by dissipation in network. The supply profile $SU(t)$ is time function of power that generation system and ESS delivers to grid. In the absence of dissipation losses, we can get the optimum power flow as the sum of storage profile $ST(t)$ and power production profile $PR(t)$ equals to the supply profile $SU(t)$ transmitting at the grid. Contrary to the ideal case, there will be dissipation loss through the ESS accounting for storage technology used, ambient temperature and conversion efficiency. Therefore, the actual power supplied is given as $a \cdot SU(t)$; where a is the scalar accounting for storage dissipation as given in Eq. 2.

$$ST(t) + PR(t) = a \cdot SU(t) \tag{2}$$

Calculation of a is not trivial and requires full understanding of the systems loss rate as a function of time. Assuming that over a window Δt ($t_1 - t_2$), a system stores negligible energy the lost energy is the difference between integrals of produced and supplied energy:

$$P_{loss} = \int_{t_1}^{t_2} PR(t) dt - a \int_{t_1}^{t_2} SU(t) dt \tag{3}$$

Equations (2) and (3) can be numerically solved for $ST(t)$ and (a) as long as P_{loss} is known and only depends on $ST(t)$. When defined as the energy supplied over energy produced over a period of time, Δt , the average system efficiency of ESS can be expressed as

$$\eta_{ESS}^{total} = \frac{a \int_{t_1}^{t_2} SU(t) dt}{\int_{t_1}^{t_2} PR(t) dt} \tag{4}$$

The revenue earned by the renewable generation or ESS of the microgrid is a function of actual supply profile $a \cdot SU(t)$ and time dependent model of electricity tariff [25]. Hence,

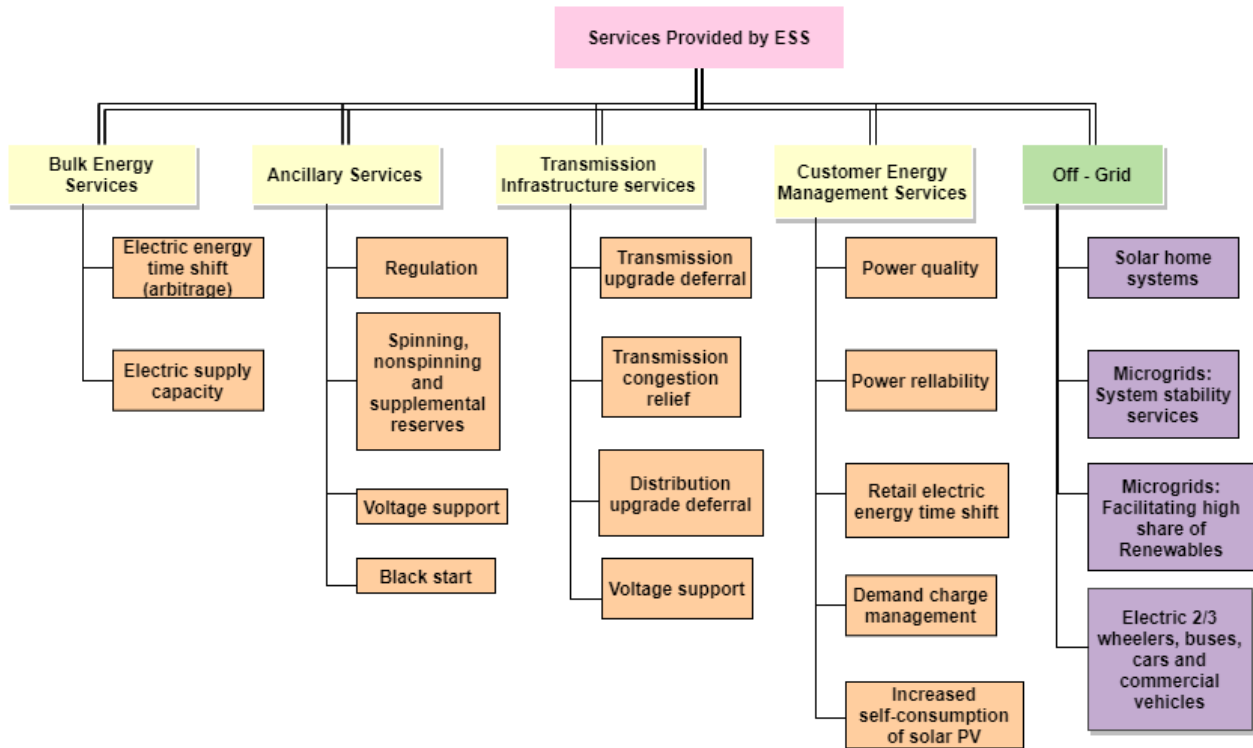


FIGURE 2. Different services based on Energy storage System.

the ESS must ensure that the desired supply profile should always be met when it is added with production profile for the efficient and reliable operation of microgrid [26].

Based on the specific storage technologies of electrical energy having unique formations and configurations, ESS can be classified into six categories: mechanical, thermal, chemical, electrochemical, electrical and hybrid systems [27]. Each system has distinguish characteristics in terms of life cycle, discharge time, discharge loss, energy density and wattage rating etc. [28]. These features play an important role to determine their suitability for different services mentioned in Fig. 2.

A. MECHANICAL STORAGE SYSTEMS

In mechanical ESS the energy is converted between mechanical and electrical energy forms. In the course of off-peak hours the electrical energy is consumed from the grid and stored mechanically (using working principle of potential energy, kinetic energy, pressurized gas and forced spring) until it is required and transmitted back to the grid [29]. Mechanical ESS are most commonly used throughout the world due to their flexibility to convert and operate stored energy when needed for mechanical work [30]. Most prevalent mechanical ESS are: pumped hydro storage (PHS), fly-wheel energy storage (FES), compressed air energy storage (CAES) and gravity energy storage systems (GES).

1) POTENTIAL HYDRO STORAGE (PHS)

The PHS systems are the largest energy storage systems of the world having 125 GW worldwide nearly 96% of the world’s

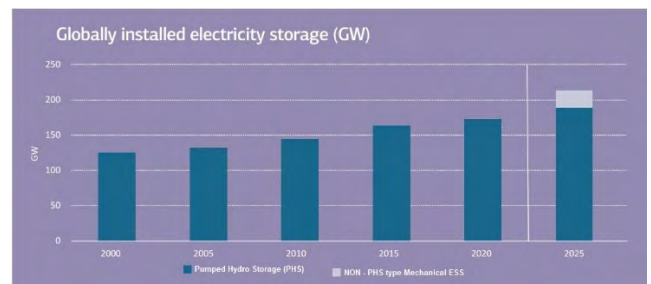


FIGURE 3. Annual increase of Pumped Hydro Storage systems [31].

electric storage capacity and 3% of the global generation capacity as shown in the Fig. 3 [31]. PHS stores the electrical energy in the form of potential energy by pumping the water from the lower side of reservoir up to the higher elevation of the reservoir. PHS power ratings ranging from 1 MW to 3000 MW operating at 76-85% efficiency having a very long life approximately 50 years or more and practically unlimited life cycles [32]. However, it is a matured technology with limitations of site-specific social boundaries, large capital investment, lengthy project construction periods, issues of habitat species conservation and 10 to 15 minutes of reaction time [33]. PHS size is another main constraint which can’t be scale down to small sizes as compared to that of new emerging ESS technologies. As shown in the Fig. 4 construction of PHS deemed to be not viable if the site is within 200-meter range of inhabited area or already existing reservoir site. The minimum average elevation of potential dam should be

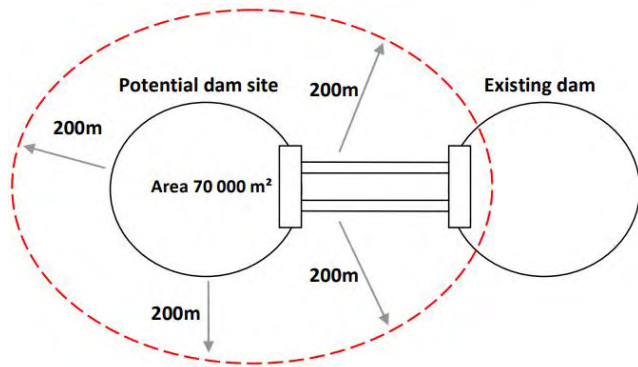


FIGURE 4. PHS minimum distance to inhabited areas [34].

150 meter above the lower reservoir [34]. Restricted geological implementations and negative environmental impacts make the future development of PHS limited [35].

2) FLYWHEEL ENERGY STORAGE (FES)

In FES system angular momentum of the flywheel mass is used to store the power in the form of kinetic energy. They are typically employed in short duration with short discharge time applications such as the requirement of power over 80 kW within a period of 1-100 s [36]. They have high power and energy density with an infinite number of charge-discharge cycles and used for stabilizing voltage and frequency [37]. The “state of charge (SoC)” of FES is a function of moment of inertia and angular speed which are readily available to measure as shown in (5).

$$E = \frac{1}{2}mr^2(w_{max}^2 - w_{min}^2) \tag{5}$$

where E is a useful energy of the flywheel in range of maximum angular speed (w_{max}) and minimum angular speed (w_{min}). Mass of flywheel concentrated at rim and radius is given by m and r respectively. The efficiency of FES system is in between 85% to 90% due to decreased mechanical friction by using magnetic bearing and very low aerodynamic resistance achieved through vacuum enclosure [38], [39]. The modern high speed flywheel systems have five main components: a flywheel, a set of bearings, an electrical motor/generator, power electronics unit and the containment system that provides high vacuum environment as shown in the Fig. 5 [39]. An integrated reversible electrical machine is mounted on the rotor. That acts as motor and draws power from grid in charging mode to accelerate the rotor shaft to working speed. Obeying the law of conservation of energy in discharging mode, the machine will act as generator by converting the kinetic energy stored in the flywheel back to the electrical energy with deceleration of rotor [40].

The amount of energy that can be stored in the flywheel is a function of moment of inertia of rotor and the speed at which it can be rotated along with its tensile strength and stress restrictions. Based on these properties they are classified into two groups: low speed steel FES systems with speeds up

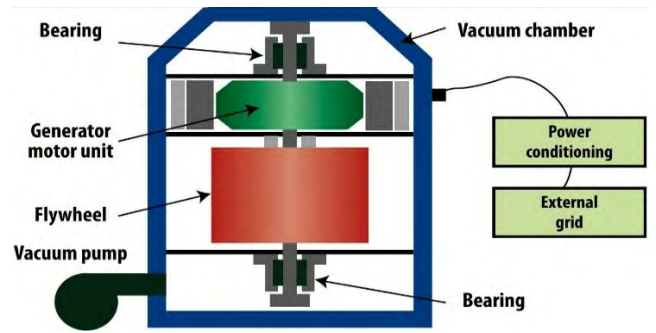


FIGURE 5. Structure and components of a FES system [10].

TABLE 1. Comparison of low speed and high speed flywheel [44].

| Specifications | Low speed FES | High speed FES |
|------------------------------|--|---|
| Material | Steel | Composite |
| Electrical machine | Induction, permanent magnet synchronous and reluctance machine | Permanent magnet synchronous and reluctance machine |
| Quarantine atmosphere | Partial vacuum and partial gas | Absolute vacuum |
| Required weight of enclosure | Double of flywheel weight | Half of flywheel weight |
| Applications | Power quality improvement | Aerospace and traction |
| Economy | Low cost and commercial | High cost and specific usage |

to 10000 rotations per minute and high-speed FES systems with speeds up to 1 lakh rotations per minute. As shown in Table 1, high speed FES systems are manufactured from advanced high speed composite materials such as carbon-fiber [36], [41]. Although low speed FES systems have very high-power density about 2000 W/kg, nevertheless, they have an average energy density of about 5 Wh/kg. They suffer from high self-discharge due to the idling losses when flywheel is on standby. Therefore, low speed FES are mainly employed in power quality applications which needing high power for short durations with high number of charge-discharge cycles. Whereas high speed FES system has very high power density along with higher energy density in the range of 200 Wh/kg. But they are not economical due to the high cost of high-speed composite materials, so, their use is limited to specific longer storage systems.

The FES systems require lower maintenance than batteries and are practically least effected by the temperature fluctuations and depth-of-discharge (DoD). They have the ability to rapidly charge-discharge within few minutes [42]. In contrast to the advantages, they suffer with high standby losses and nearly 20% of self-discharge per hour occurs in the stored capacity. Any unexpected dynamic load or external shock can lead to system failure [10]. FES systems are still not considered as mature technology and require further research and development in different domains of rotating parts of FES [31], [43]. Besides that, they are costly and relatively

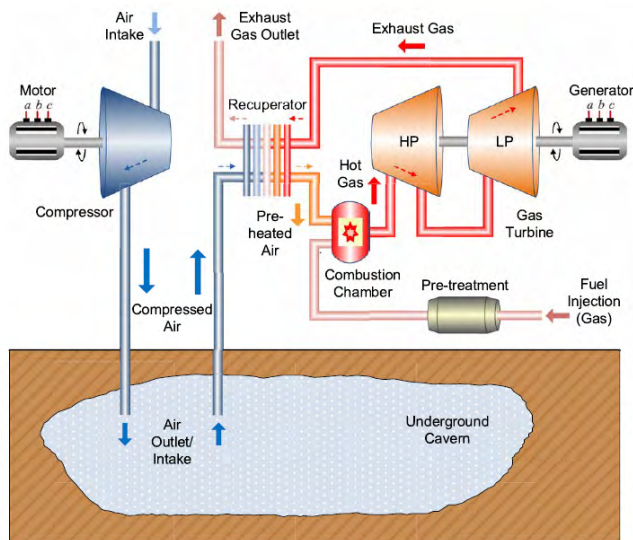


FIGURE 6. Large scale diabatic in-ground cavern CAES system [46].

behind in commercial success [43]. Overcoming these limitations will improve the round-trip efficiency of the system and makes the FES system highly reliable with improved power stability and reduced CO₂ emissions.

3) COMPRESSED-AIR ENERGY STORAGE (CAES) SYSTEMS

The CAES system stores the energy in the form of intermolecular gas pressure with compression of air into the reservoir, then converts it into the modified gas. Compressed modified gas is expanded to rotate the turbine coupled with generator for producing electricity [45]. CAES systems can be realistic alternative to the PHS systems because of their large capacity, intermediate geographical dependency, longer lifespan and low cost per kW [46]. Based on the exothermic and endothermic processes involved, in the compression and expansion of the air and heat exchange, the complex designs of the CAES systems are classified into three types: Isothermal storage, adiabatic storage systems and diabatic storage systems [47]. Isothermal and adiabatic systems work well for small power density requirements whereas diabatic storage systems are the most commercially implemented CAES systems due high-power density and great system flexibility. As shown in the Fig. 6 in diabatic CAES systems external power source is used to heat or cool the air to maintain the required temperature of the system, thus, the efficiency is also increased.

Similar to the principle of conventional gas turbine power plant the diabatic CAES system works with one major difference: the compression and expansion phases of CAES are decoupled rather than simultaneous. In charging mode, the excess or off-peak power is consumed to drive the chain of motors for compressing the air into gas reservoir (which is preferably underground cavern). The reservoir will be an air tight space such as conditioned old salt reservoirs or depleted gas fields, since constructing the metal vessel cavern will

significantly increase the storage costs. The typical pressure of reservoir is maintained between 4.0 megapascals to 8.0 megapascals [48]. The heat developed while compressing the air is pulled out by the radiator into atmosphere. In discharging mode of CAES system, the compressed air duly heated up by combustion chamber and is expanded through a high-pressure turbine. Now, the air is mixed with fuel and combusted through the exhaust expanded to low pressure turbine. Both high pressure and low pressure turbines are simultaneously coupled to the electrical generator for producing electricity [49]. The classic design of CAES system involves the limitation of fossil fuel combustion and CO₂ emission. Therefore, advanced adiabatic CAES systems are developed to address this problem, where thermal storage system is integrated with CAES system to produce electricity without involvement of combustion process [50]. The efficiency of the plant is achieved up to 70% and has recently emerged as optimal solution for medium and small scale applications [48].

The installed commercial capacity of the CAES systems ranges from 35 to 300 MW with notable applications of grid support such as: load levelling and voltage and frequency control [51]. The recent developments in the hybrid CAES plants with off shore and on shore wind plants shows increased overall efficiency with reduced fluctuations in the power output [52]. The major barrier in CAES technology is the suitable geographical location of air storage tank or underground cavern. To overcome this limitation recently high pressure over ground carbon fiber tank air storage is proposed for small and medium scale advanced adiabatic CAES systems [53], [54]. Alternative low cost CAES solution could be achieved by decentralized small scale CAES systems, which is formed by collection of installations to serve as a virtual large power plant that is controlled by central unit of distribution system [55]. Distributed operation and control will improve their efficiency and flexibility to supply electricity to the remote locations that are not easily accessible [55]. In this regard, some studies on development of wind turbines with small scale CAES system are being carried out by University of Birmingham [56].

B. ELECTROSTATIC AND MAGNETIC ENERGY STORAGE SYSTEMS

Storing of electrical energy directly in the form of charge and producing the electrical power back when required, is possible by electrostatic and magnetic energy storage systems (EMESS) [32]. Supercapacitors and superconducting magnets are used to store the energy in the form of electrostatic and magnetic fields. These are high power and medium energy density storage devices which help in accommodating the peak energy consumption, smoothing the output power and energy recovery in mass transit systems [57]. The EMESS systems mainly contains super capacitor energy storage (SCES) and super conducting magnetic energy storage (SMES).

1) SUPER CAPACITOR ENERGY STORAGE (SCES)

They are also called as ultra-capacitor energy storage (UCES) or electric double layer capacitor (EDLC). They store energy in the form of electrostatic field produced due to constant dc voltage applied between two electrodes which are separated by thin layer of insulator or dielectric medium [58]. Independent of any chemical reactions SCES are capable of quick charge with high currents in addition to characteristics of high specific energy, low internal resistance and wide temperature range, which makes them substitute to conventional capacitors employed in power electronics and storage batteries [59], [60]. Through proper control strategy, the pulsed power load demands of spacecraft, electromagnetic launch weapons and ships with high power radar can be smoothly met by SCES system subsequently avoiding any thermal and power disturbances on microgrid [61].

Apart from same physical principle, the key structural difference of the SCES and classical capacitors is extremely high specific surface area of SCES formed due to the use of liquid electrolyte and porous carbon electrodes. Moreover, the extremely short gap (of the order 1nm) between the electrode and electrolyte makes SCES systems capable of very high capacitance values of order many thousand farads [62]. Based on the materials of electrodes employed there are two types of SCES systems: symmetrical and asymmetrical SCES systems. In symmetrical SCES system both the electrodes are made up of same material (activated carbon) whereas in asymmetrical SCES systems one of the electrodes is made up of metal (nickel hydroxide) which considerably increase the energy density and decreases the leakage currents. Symmetrical SCES systems are preferred in small and medium scale applications whereas asymmetrical SCES are preferred for large-scale applications [63], [64]. As shown in the Fig. 7 the SCES system have porous electrodes of activated carbon immersed into an electrolyte of potassium hydroxide or sulfuric acid. To prevent the physical contact of the electrodes, a porous membrane is placed between them through which ions transfer. Electric charge will get deposited at the intersections of porous electrodes and liquid electrolytic solution as shown in Fig. 7. Therefore, a series connected double layer capacitor is created between two electrodes and electrolyte [65].

Various SCES systems are available with power ratings in range of 10-75 kW through energy ratings of 4-70 Wh, with no trouble they can be connected in series or parallel for collective capacity [67]. The specific energy density of the super capacitor is around 5 Wh/kg considerably larger than that of normal capacitors nevertheless it is only 10% of the electrochemical batteries. Whereas the specific power density of super capacitors is 10 to 100 times superior than electrochemical batteries [68]. Major advantages of SCES system include robustness, reliability, adoptability for diverse environments (hot, cold and moist), unaffected by DoD, independent of maintenance and very long life cycles nearly 10000 fully charge-discharge duty cycles with approximate of 95% round trip overall efficiency [69]. On the contrary

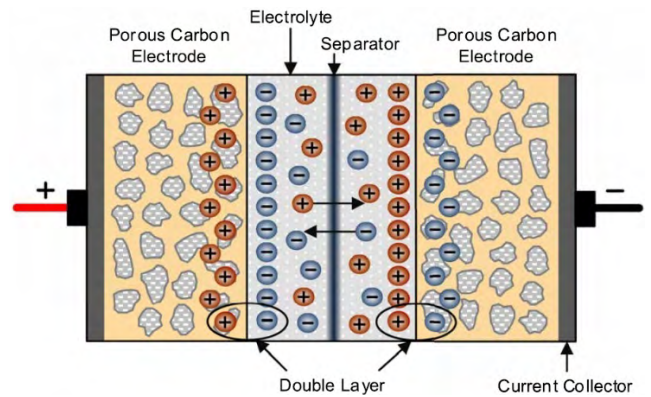


FIGURE 7. Graphical representation of symmetrical SCES [66].

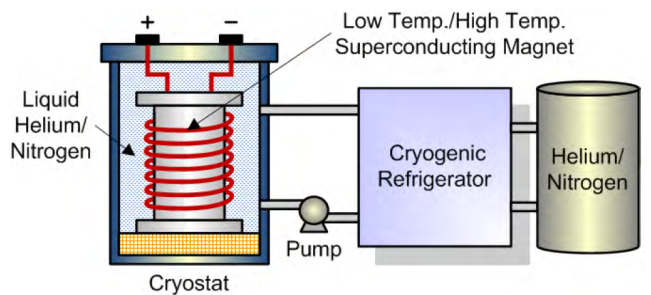


FIGURE 8. Super magnetic energy storage (SMES) system design [66].

the SCES suffers from very high self-discharge rate of order 10 - 40 % of energy storage per day and the capital cost of SCES system is also very high.

2) SUPER MAGNETIC ENERGY STORAGE (SMES)

The electrical energy stored in SMES is in the form of magnetic field of superconducting coil formed due to flow of direct current. The ohmic losses in SMES once charged are virtually zero due to negligible resistance of superconducting coil [70]. The cryogenic cooling of coil is employed in SMES to cool it below its superconducting critical temperature. While in discharging mode, the SMES is capable of releasing very high power (several megawatts) into the electric network within few milliseconds time. Advanced low temperature and high ductile characteristic superconductor material such as niobium-titanium (NbTi) fine coils together with liquid helium coolant or superfluid helium coolant at 4.2 K are employed in SMES design [71]. In accordance with the basic principle of SMES, when superconductor is charged while the cryogenic temperature is kept below the critical value, the energy will be stored permanently without any current decay [72]. As shown in Fig. 8 the basic design of SMES consists of superconductor coil, refrigerator system and power conditioning system.

Based on type of superconductor material and cryogenic conditioning system the SMES are classified into two groups: low temperature superconductor (LTS) SMES systems built with NbTi superconductor and liquid helium coolant at 4.3 K,

whereas high temperature superconductor (HTS) SMES systems are built from ceramic oxide superconductor and liquid nitrogen coolant at 77 K. HTS SMES systems are cost effective and economical than the LTS SMES systems [73]. The overall energy stored in superconductor coil of SMES is given by (6):

$$E = \frac{1}{2} Li^2 \quad (6)$$

where, L is the coil inductance based upon the geometry and cross-sectional area of the wire, i is the amount of current flowing in the coil having energy E . In accordance with the advanced large designs, the geometry of SMES system is of solenoidal or toroidal structure constituting refrigerator system and power conditioning system inside them [74], [75]. Solenoidal structure is simple and stores large amount of energy per unit length nevertheless the negative side is they produce stray magnetic fields which have impact on power electronic devices and cryogenic refrigerators installed. Thus, they are installed at distant sites with proper shielding. In contrast, the energy stored in per unit length of toroidal structure is half of solenoidal superconductor, but the amount of stray magnetic field is reduced drastically. The SMES systems can provide fast response charge and discharge of very high power density (up to 5000 MWh) along with high efficiency of order 95%-98% having approximate lifetime of 30 years [76]. Other applications include black start capacity and replacement of major unit trips. SMES system can absorb the ramp and transients in a very quick rate, there by the power system units can be operated at maximum efficiency optimum points. The complicated cooling system and high capital investment are major setback of SMES system. The susceptibility of temperature variations and critical magnetic field is troublesome for stability of superconducting coil. Although LTS SMES is commercially advanced whereas HTS SMES are still unindustrialized and are not entirely mature technology [77]. Moreover, in microgrid applications the SMES can be used to exchange the real and reactive powers. Multiple hybrid SMES applications in distributed grid architectures and transportation technology are under development for designing vehicular and current source grid inverters [78], [79].

C. THERMAL ENERGY STORAGE (TES) SYSTEMS

TES is significantly used technology around the world, according to U.S department of energy report the TES installed capacity is 3.3 GW accounting for 1.9% of the world energy storage in 2017 [80]. As the heating and cooling necessities signify 45% of the total domestic and commercial energy usage, TES systems can be of significant support to load shifting and heating/cooling requirements of industrial and domestic sector, thus participating in demand side management of the respective microgrid [81]. The TES system consists of three major parts: thermal storage tank, heat transfer mechanism (refrigeration system, heat flowing channels, pumps) and containment control system. At first the

accessible heat is stored in an insulated repository (storage reservoir) using distinctive technologies. Stored heat is extracted by heat transfer mechanism through directly or indirectly for usage of heat energy or for generation of electricity by heat engine cycle [43]. The insulation and operation of storage reservoir and heat transfer medium is monitored by containment control system [82]. Though the total cycle efficiency of TES system is low at 30%-50%, the advantages such as: daily self-discharge nearly equal to ($\sim 1\%$), good energy density (specific energy 80-250 Wh/kg), environment friendliness together with low capital cost investment makes the TES system optimum choice for large energy storage without any major hazards in many applications [43], [83].

Depending upon the operating temperature of energy storage material, TES technologies are categorized into two groups: low temperature TES and high temperature TES [43]. Low temperature TES system consists of auriferous low temperature storage and cryogenic energy storage systems. Water cooling and reheating process is used in auriferous low temperature TES while liquid nitrogen or liquid air expansion ratio is used in cryogenic energy storage TES systems, such as liquid air energy storage (LAES).

Low temperature TES is more suitable for high power density applications such as: load shaving, industrial cooling and future grid power management. Sensible heat and latent heat TES systems are most important in high temperature TES systems. In sensible heat storage system, the thermal energy is stored with change of temperature in storage medium without undergoing any form of phase change in the material. The capacity of sensible heat storage system depends upon the specific heat and mass of the storage medium, which may be of different form, such as liquid (water, molten salt or thermal oil) or solid (concrete, stone, metal or ground) [85]. Major setback of sensible heat storage systems is large space requirement. In the latent heat storage system the energy is swapped during the phase change of the materials through metallic fillers or metal matrix structures [84]. Based on the combinations, phase change materials (PCMs) are classified into three types: solid-solid, solid-liquid and liquid-gas PCMs. The solid-liquid PCMs are the most suitable for the TES systems. In solid-liquid PCMs we have organic (paraffin, fatty acids), inorganic (salt hydrates, metallics) and eutectics type of materials. The advantages and disadvantages of these three types of PCMs are listed in Table 2. As given in [82], the energy stored in mass m of the solid-liquid transition PCM is given by equation (7):

$$Q = m [c_{ps}(T_m - T_s) + h + c_{pl}(T_l - T_m)] \quad (7)$$

where, c_{ps} and c_{pl} are the specific heats of the solid and liquid phases respectively, h is phase change enthalpy and T_m , T_s , T_l are the melting temperature, solid temperature and liquid temperature respectively.

The melting temperature and phase change enthalpy of PCMs will decide the storage capacity of the system. They are also called as "hidden heat storage systems" because here the rate of change of temperature during energy exchange is

TABLE 2. Comparison of different PCMs [84].

| Classification | Advantages | Disadvantages |
|----------------|---|--|
| Organic PCMs | <ol style="list-style-type: none"> 1. Availability in large temperature range. 2. High heat of fusion. 3. No supercooling. 4. Chemically stable and recyclable. 5. Compatibility with other materials. | <ol style="list-style-type: none"> 1. Low thermal conductivity. 2. Relatively large volume change. 3. Flammability. |
| Inorganic PCMs | <ol style="list-style-type: none"> 1. High heat fusion. 2. High thermal conductivity. 3. Low volume change. 4. Low cost. | <ol style="list-style-type: none"> 1. Supercooling. 2. Corrosion. |
| Eutectics | <ol style="list-style-type: none"> 1. Sharp melting temperature. 2. High thermal storage density. | Unavailability of current physical data of thermo-physical properties. |

zero [46]. Latent heat systems have high storage density even for small storage reservoir, more efficient and economical than sensible heat systems. Therefore, they can be easily adopted as distributed energy resources in buildings. For example, in advanced concentrated solar power (CSP) plants with two tanks of molten salt storage, each one for sensible heat and latent heat are used to store the thermal energy of solar thermal input at 500° C and 285° C respectively [82]. A wide range of low melting point, high temperature and low cost distributed TES plant methods such as: quartz glass, room temperature ionic liquids, high purity graphite, phase change materials, rock bed storage and saturated water/steam storage methods at the temperature range of 400-1000 °C can be employed in the future smart grid [86].

D. CHEMICAL ENERGY STORAGE (CES) SYSTEMS

Chemical energy storage (CES) systems are the important long-term energy storage systems in the form of chemical bonds of molecular compounds. The rearrangement of these molecules through electron transfer chemical reactions will produce the power. The primary substance from which the energy is recovered will convert into totally new substance or into another form of energy. CES is environment friendly and zero emission technology with storage capacity of more than 100 GWh [87]. In CES the typical task of continuous electrical energy generation from that of the chemical energy fuel is done by fuel cell (FC). Unlike that of battery system the FC will continuously supply the electricity as long as the externally supplied active fuel and oxidant are available, reducing the dependency on fossil fuel consumption by decreasing harmful gas emissions [88]. The anode in FC is composed of liquid or gaseous fuel and cathode can be air, oxygen or chlorine oxidant [89]. Significant amount of energy can be stored in FC by optimizing the size of hydrogen storage tank, independent of power rating. Hydrogen FC can be applied to distributed microgrid power generation scenario

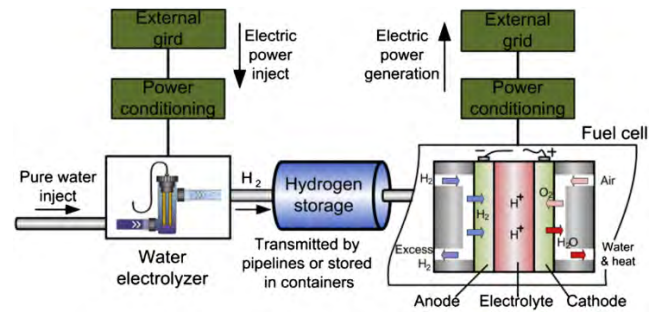
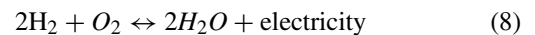


FIGURE 9. Regenerative hydrogen Fuel Cell system topology [83].

and automobile industry, releasing only water vapor in the environment. FC technology is major technique of hydrogen utilization, in which hydrogen or synthetic gas will be energy carrier and electrolyzed hydrogen can also be synthesized into methane (natural gas) with carbon dioxide [87]. FCs are direct and indirect systems based upon the direct reaction of fuel (e.g., hydrogen or methanol) and indirect conversion of fuel (e.g., natural gas or fossil fuels) into enrich hydrogen gas before FC reaction respectively [90]. In discharging mode hydrogen FC use the mixture of hydrogen and oxygen to produce electricity for long term and seasonal applications. While in charging mode hydrogen FC will decomposes the water (H₂O) into hydrogen (H₂) and oxygen (O₂) through electricity. Then, the H₂ will be stored in high pressure vessels for long duration which can be transmitted back by pipelines to the fuel cell chamber as shown in Fig. 9. The overall chemical reaction of FC is given by equation (8).



When the hydrogen fuel and oxygen are passed through the catalytic surface of the fuel cell electrodes, hydrogen ions and free electrons are produced. Hydrogen ions (H⁺) from anode are collected at the oxygen electrode flowing through the electrolyte. At the same time, the free electrons will flow through the power circuit connected externally. As a result, an oxidation half reaction and reduction half reaction at anode and cathode respectively release water and heat by combining hydrogen ions, oxygen and electrons [24]. As shown in the Fig. 9, a pure water electrolyzer will separate the hydrogen and oxygen continuously which is fed back to the H₂ storage tank. The recycling closed loop process continues practically for unlimited time to meet the load [91]. Based upon the combinations of fuel type, oxidant, electrolyte type, ambient temperature and application specification the hydrogen FCs are classified into as six types: alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), solid polymer fuel cell-proton exchange membrane FC (SPFC-PEMFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC) and direct methanol fuel cell (DMFC) [92]. Table 3 summarizes their technical specifications and specific applications of each major FC.

Unlike the harmful by-products released by gasoline-based vehicles, the hydrogen-based FC vehicles will have least

TABLE 3. Operational specifications of major fuel cell technologies [92].

| Fuel Cell | Fuel | Oxidant | Cell voltage | Applications |
|-----------|--|-----------------------|--------------|--|
| AFC | Pure H ₂ | O ₂ in air | 1.0 | Military, Space crafts |
| PAFC | Pure H ₂ | O ₂ in air | 1.1 | Distributed generation |
| SOFC | H ₂ , CO, CH ₄ , other | O ₂ in air | 0.8-1.0 | Power utility storage and distributed generation |
| MCFC | H ₂ , CO, CH ₄ , other | O ₂ in air | 0.7-1.0 | Power utility storage and distributed generation |
| PEMFC | Pure H ₂ | O ₂ in air | 1.1 | Backup power and small distributed level |
| DMFC | CH ₃ OH | O ₂ in air | 0.2-0.4 | Electric vehicles, Transportation vehicles. |

environmental impacts as their by-products are only heat and water. Nevertheless, the overall low conversion efficiency of CES system, i.e. 40%-50%, high upfront cost of hydrogen refueling, lack of existing infrastructure and low safety measures makes it unsuitable for large scale fundamental energy system [93]. The essential element of hydrogen FC is the hydrogen storage system which is major part in determining cost and safety. Solar hydrogen approach is under early stage of development, where the concentrated solar radiation is used in thermo chemical gasification cycles to extract the hydrogen from thermochemical methods directly without using electricity [43].

E. ELECTROCHEMICAL STORAGE SYSTEMS (EcSS)

Electrochemical energy storage systems (EcSS) are the oldest energy storing technologies where a reversible chemical reaction in the active material through electrolyte is used for producing/storing of DC power. All conventional secondary (rechargeable) battery energy storage (BES) and flow batteries (FBs) stores the electrical energy in the form of chemical energy comes under EcSS [91]. EcSS are the largest group of electrical energy storage systems available with wide range of energy densities in the range of 10 Wh/kg up to 13 kW/kg having efficiencies of 70-80% for various methods without any harmful emissions and minimum maintenance [94], [95]. Batteries are mature technology for shorter duration storage with back up feasibility of one second to around five hours. Due to their availability in various sizes and system mobility features, EcSS are commercially successful in grid scale utility applications, residential and commercial buildings [96].

In order to get the desired voltage/power rating, a number of electrochemical cells are connected in series or in parallel in BES system. Each cell has two electrodes: anode (participating in oxidation reaction by losing electrons) and cathode (simultaneously participating in reduction reaction by gaining electrons) along with an electrolyte in the form of

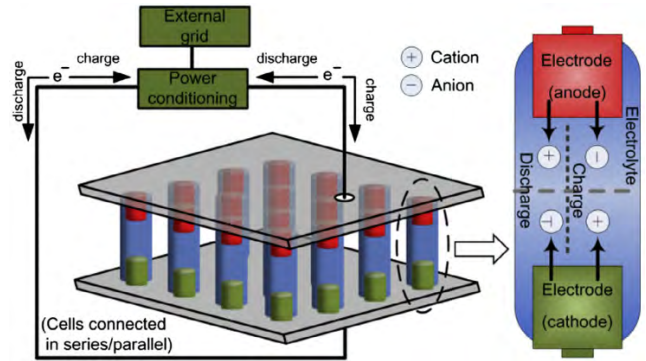


FIGURE 10. Schematic of BES system with multiple cells [83].

TABLE 4. List of standard reduction potential of chemicals in BES [98].

| Reduction Half-Reaction | Standard Electrode Potential (V) |
|---|----------------------------------|
| $F_2(g)+2e^- \rightarrow 2F^-(aq)$ | +2.87 |
| $S_2O_8^{2-}(aq)+2e^- \rightarrow 2SO_4^{2-}(aq)$ | +2.01 |
| $O_2(g)+4H^+(aq)+4e^- \rightarrow 2H_2O(l)$ | +1.23 |
| $Br_2(l)+2e^- \rightarrow 2Br^-(aq)$ | +1.09 |
| $Ag^+(aq)+e^- \rightarrow Ag(s)$ | +0.80 |
| $Fe^{3+}(aq)+e^- \rightarrow Fe^{2+}(aq)$ | +0.77 |
| $I_2(l)+2e^- \rightarrow 2I^-(aq)$ | +0.54 |
| $Cu^{2+}(aq)+2e^- \rightarrow Cu(s)$ | +0.34 |
| $Sn^{4+}(aq)+2e^- \rightarrow Sn^{2+}(aq)$ | +0.15 |
| $S(s)+2H^+(aq)+2e^- \rightarrow H_2S(g)$ | +0.14 |
| $2H^+(aq)+2e^- \rightarrow H_2(g)$ | 0.00 |
| $Sn^{2+}(aq)+2e^- \rightarrow Sn(s)$ | -0.14 |
| $V^{3+}(aq)+e^- \rightarrow V^{2+}(aq)$ | -0.26 |
| $Fe^{2+}(aq)+2e^- \rightarrow Fe(s)$ | -0.44 |
| $Cr^{3+}(aq)+3e^- \rightarrow Cr(s)$ | -0.74 |
| $Zn^{2+}(aq)+2e^- \rightarrow Zn(s)$ | -0.76 |
| $Mn^{2+}(aq)+2e^- \rightarrow Mn(s)$ | -1.18 |
| $Na^+(aq)+e^- \rightarrow Na(s)$ | -2.71 |
| $Li^+(aq)+e^- \rightarrow Li(s)$ | -3.04 |

solid, liquid or viscous state according to requirement [24]. In discharging mode, electrochemical reactions of oxidation and reduction flows the electrons to external power circuit. While in charging mode the external voltage applied between electrodes restores the chemical energy by reversible reaction as shown in the Fig. 10 [97]. In order to get the required potential in standard electrochemical cell, selecting the appropriate anode (oxidizing material) and cathode (reducing material) is vital part of cell design. Table 4 lists the standard reduction potentials in decreasing order. When two materials present in the list are coupled in a electrochemical cell, due to the chemical tendency of standard electrode potential, the one at top will become cathode (reduced) and the one at bottom will become anode (oxidized) [98].

BES efficiently assist in most of stationary and mobile applications, providing flexible range of power densities (90 kW/m³ to 10 MW/m³) and energy densities (75 kWh/m³

to 800 kWh/m³) [99]. BES are also employed for frequency regulation and stabilization of current/voltage fluctuations in grid and utility energy management systems [87]. In implementation of large scale BES the major barriers are low cycling times and high maintenance cost, though large scale stationary BES systems are commercially available today such as: Pb-acid, NiCd, ZnBr and Li-ion batteries [95]. Nevertheless, very high power, long life time, robust and economical BES technology are currently in research stage which can meet the demand of grid size performance requirements [100]. In contrast to the advantage of relatively short construction period (approximately 12 months) many BES suffer from challenges of toxic chemical material disposal or recycling of dumped batteries and small DoD in order to have to large life time [101].

Many different types of BES systems exist which can be broadly classified into two groups: storage integrated BES systems (e.g. lead-acid, lithium-ion, sodium-sulfur, nickel-cadmium and nickel-metal hydrate batteries) and external storage BES systems (e.g. vanadium redox flow, ZnBr and Zn-air systems). In storage integrated BES systems there is no spatial parting between energy conversion unit and active material where charge/discharge occurs directly. While in external storage BES systems, the energy conversion unit and active material are physically separated with each other. Unlike in storage integrated BES systems where power and energy ratings are relative to energy storing capacity, the external storage BES systems are independent of size and ratings for power and energy as needed [102]. Among the many types of BES systems available we cannot state univocally that particular BES is better than others as no BES technology ranks top in all technical parameters required by load. Depending upon the application power and energy ratings, size, weight, response time, DoD, operating temperature and ambient temperature, an unique decision will be taken for corresponding case [99]. Following subsections covers description of several important BES technologies available today.

1) LEAD ACID (PbA) BATTERIES

Lead batteries are oldest rechargeable batteries invented in the year 1859 by physicist G. Plante. They are mature technology offering the energy storage with good cost-performance ratio (sized from 1 Ah to ~1000 Ah), small daily self-discharge rate (<0.3%) and fast response times. They are natural choice for several applications because of their ruggedness, safe operation, temperature tolerance, very good cycle efficiencies (~63-90%), low maintenance and low capital costs [103]. In data and telecommunication systems, emergency power supply, grid utility applications, renewable energy output smoothening and in hybrid electric vehicles lead acid batteries are used as backup power supply in range of kW to tens of MWs [103], [104]. The life time of lead acid battery mainly depends upon the ambient temperature, current rates for charging/discharging and number of times it is charged and discharged. A series or parallel connection is used to get

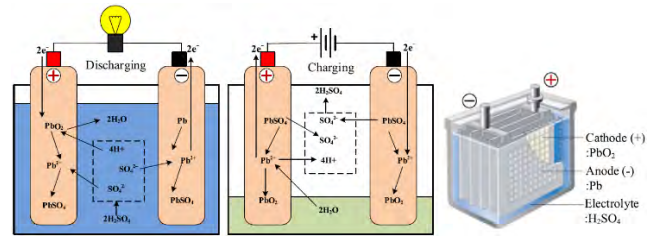
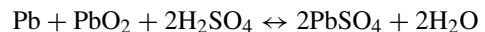


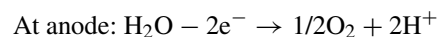
FIGURE 11. Lead Acid battery prototype during charging and discharging [27].

the required power and energy ratings. Typically, each cell voltage of lead acid battery is 2.15 V and current charging rates are at 0.25 to 4 C-rates [105]. The basic structure of the lead acid battery is shown in the Fig. 11. The electrodes constitute of lead dioxide (PbO₂) as anode and plates of lead (Pb) with high surface area as negative electrode i.e., cathode which are immersed in the electrolytic solution of sulfuric acid (H₂SO₄).

The electrochemical reaction taken place inside the lead acid battery is also called as double sulfate reaction. During discharging process, the oxidation reaction at anode (Pb → Pb²⁺ + 2e⁻) and reduction reaction at cathode (Pb⁴⁺ + 2e⁻ → Pb²⁺) results in formation of PbSO₄ at both the electrodes, which produces the electricity due to flow of free electrons in external power circuit [95]. This process is reversible under the charging conditions as described by the overall electrochemical reaction given below.



From the equation we can see that the electrolyte (H₂SO₄) is used to produce the PbSO₄ and H₂O during energy discharge, the state of charge can be measured by determining the relative density of the sulfuric acid. Hence, the quality of H₂SO₄ present in the cell is additional component that effects the electrochemical performance of system. Over charging and discharging will lead to poor cycle efficiency of the lead acid batteries. In case of overcharging i.e., exceeding the cell voltage value to ~2.39V, the electrolyte will decompose as:



Which causes the loss of water in electrolyte, which needs to be added for or as maintenance. Where as in case of over discharging a sulphate layer will be formed on the cathode electrode which cannot be reversed during the recharging process. Ultimately reducing the life cycle of the battery by limiting the surface area participating in the electrochemical reaction. Also, at high discharging rates, evolution of hydrogen takes place which reduces the efficiency and leads to possibility of explosion hazards [106]. Research is going on to increase the life cycle of the lead acid battery by inclusion of carbon in small concentration (0.15—0.25 percentage with respect to weight) to avoid the accumulation of sulphate layer at cathode. Split design lead—carbon (PbC) usage as

negative electrode results in 50-60% increase in charge/discharge power ratings [107].

Two categories of lead acid batteries are available in market today, namely: flooded (vented) lead acid batteries (VLA) and valve regulated (sealed) lead acid batteries (VRLA/SLA). VLA batteries require frequent water replenishment for its working or operation. Comparatively, the size and ratings of VLA batteries will be larger than that of VRLA batteries, since the provision of external ventilation and water replacement is available in VLA. The performance of VLA battery during charging/discharging is further increased by addition of the copper stretch mesh into the negative electrode for decreasing the internal resistance [10]. The VRLA batteries are recognized as maintenance free batteries, because of elimination of water replacement process inside of battery. In order to recombine the oxygen (which is generated while charging) during discharging to form water, a pressure release valve is arranged in VRLA batteries which maintains the oxygen pressure inside the battery. The VRLA batteries are available in small and compact sizes and can be applied in areas where ventilation is not available. High specific power and rapid charging characteristics of VRLA are more vulnerable to fail due to high temperature than VLA batteries [43], [108]. Deterioration of positive plate takes place when VRLA batteries are operated in float charging mode, consequently their installation at substations will become difficult [105], [109]. Further, the VRLA batteries are available in two unique models: absorbed glass mat design (AGM) batteries and gelled electrolyte (GEL) batteries. A glass fiber is used in AGM, reducing the evaporation to great extent and is fully sealed externally. The fiber is soaked in electrolyte before inserting and acts a solid isolator between electrodes which helps it to be easily installed in portable devices. While in GEL batteries a silica gel is used which considerably increases the operating temperature of battery and it's ruggedness [83], [110].

Though, they suffer with relatively low energy density (50-90Wh/L), heavy in weight, low cycle life (nearly ~2000), long charging time, degradation when high power is drawn (specific power about 180 W/kg), periodic water maintenance, premature failures due to sulfidation and toxic nature of lead restricted their applications. Furthermore, their performance degraded at low temperatures, thus thermal management system needs to be installed which increases the cost and also to control the sulfidation acceleration, a floating temperature higher than the nominal value is to be maintained and should not be discharged below 1.75 V per cell [46]. But the market availability of lead acid batteries is wide and nearly 97% of the lead in the used batteries can be recycled efficiently [10], [95]. In comparison to other batteries, lead acid systems have good charge/discharge characteristics below the freezing temperatures (up to -20°C/-4°F) but the charging should be at rate of 0.3C charge [111].

2) LITHIUM-ION (LI-ION) BATTERIES

Lithium ion batteries works on the principle of reversible extraction of ions on the porous electrodes having a foil in

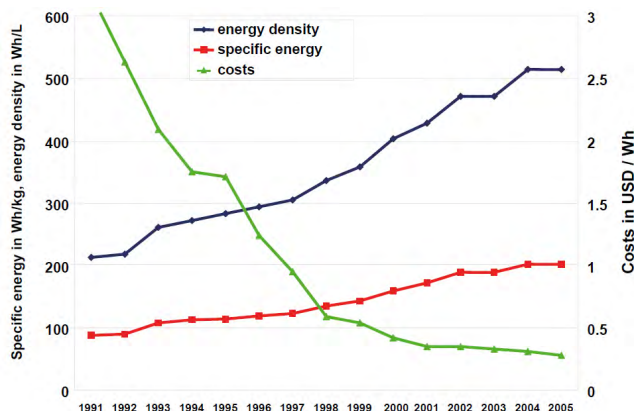


FIGURE 12. Development of specific energy and energy density with respect to cost per watt-hour of Li-ion batteries [10].

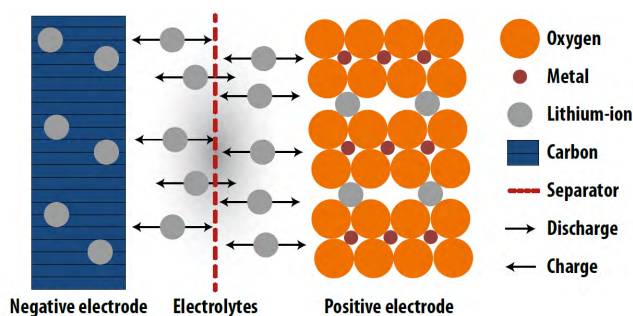


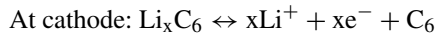
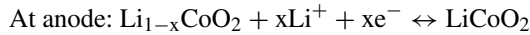
FIGURE 13. Schematic of Li-ion cell components and principle [10].

between them in order to make electrical isolation [112], these electrodes and foil are immersed into the electrolytic solution of Li^+ ions before extraction. Due to the high energy density (6 to 8 times of the VLA batteries) with respect to per unit volume (75-200 Wh/kg), stable cycle, low self-discharge rate (<8% per month), long life cycle, light weight, fast charge/discharge, rapid response time (in milliseconds) and high efficiency of the Li-ion batteries, they became workhorse battery in portable electronics having wide range of market applications [86], [113]. As shown in Fig. 12 over the years there is significant decrease in the cost with respect to the increase in energy density and specific power of Li-ion batterie, hence less material is required for the manufacturing of same amount of energy cell. Also, compact Li-ion batteries available are hermitically sealed and maintenance free, as the possibility of gas evolution and electrolysis is zero due to absence of water in chemistry of Li-ion battery [109].

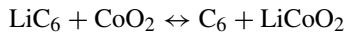
The Li-ion batteries primarily made up of lithium ion and lithium polymer. Each cell of the Li-ion battery is having the voltage of ~4 V having prismatic or cylindrical structure [95]. As shown in Fig. 13 during the discharging process the Li-ion passes from anode (layered graphite carbon) to the cathode (lithiated metal oxide), such as:

LiCoO_2 , LiNiO_2 and LiMO_2 through the electrolyte of dissolved lithium salts in organic carbonates. While charging process this phenomenon is reversed, as Li^+ ions travels

from cathode to anode via electrolyte and reduction reaction takes place to form the lithium atoms which are deposited in between the carbon layers of electrode [95]. The electrochemical reactions that takes place are given as:



Overall chemical reaction is:



Based on anode chemistry, Li-ion batteries are classified into lithium cobalt oxide (LiCoO_2), lithium manganese oxide (LiMn_2O_2), Lithium iron phosphate (LiFePO_4), Lithium nickel manganese cobalt oxide (LiNiMnCoO_2) and Lithium Titanite ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) batteries [108]. In which nickel and manganese oxide batteries are economically effective with respect to the basic lithium cobalt oxide batterie. Among all of the lithium ion batteries the iron phosphate batteries are considered to be most economical beside having high power density and discharge current capability. They are widely applied in EVs due to their reliable chemical and thermal characteristics. Lithium titanite batteries are attractive for powering the present and future EVs in recent years due to their fast charging characteristics [114]. Moreover, research is going for reducing the manufacturing cost of lithium batteries with low cost battery materials and energy management system [115]. The lifetime of Li-ion batteries is sensitive towards over discharging, high temperatures typically above 45°C and aging. While in charged conditions Li-ion batteries are extremely sensitive to high temperatures, over charging and internal pressure build up and cases of laptop and computer explosion also reported. This makes the possibility of large size utility plant very low although they are affordable in many aspects [116].

Lithium Polymer (Li-polymer) batteries are basically similar to the Li-ion batteries where the organic electrolyte is replaced by the dry polymer one which encapsulates the electrodes also. They are specifically designed for telecommunication applications having specific energy (155 Wh/kg) with increased safety and least flammability. The conductivity of polymer electrolyte is increased while ambient temperature is increased typically at $60\text{--}80^\circ\text{C}$, hence the life expectancy is increased under variable conditions. However, they suffer with low conductivity and power density problems [109]. Distinct form Li-ion cell designs such as: prismatic and cylindrical, the Li-polymer designs are soft in package or pouch. Therefore, according to the requirement of mobile phones or notebook their shape can be manufactured [66]. At present more than 300 MW utility scale high power and short duration Li-ion battery projects are installed worldwide for application of frequency control in addition to the microgrid integration support for the high power intermittent renewable energy resources, especially in islanded mode of operation [67]. Lithium iron phosphate and lithium sulfur batteries can be good alternative in microgrid due to their reliability, low cost, high specific energy and decreased

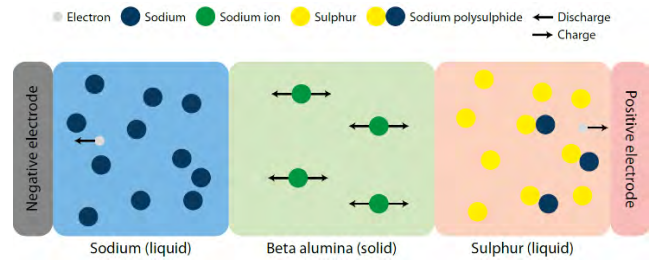


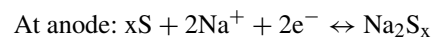
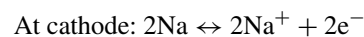
FIGURE 14. Electrochemistry of the Na-S battery [10].

environmental risks [117]. In [105] the Li-ion batteries are proposed to be more advantageous for long-term operational life stationary applications when compared with lead acid batteries in terms of efficiency, charging/discharging performance and cost analysis except at sub-freezing temperature applications. Irreversible plating of liquid lithium develops on anode of Li-ion cells if charging is done under sub-freezing (less than 0°C) temperatures, which can cause the thermal runaway and flames burning out. Therefore, under subfreezing temperature lead acid batteries have more tolerance and safer than Li-ion batteries [105], [111].

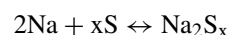
3) SODIUM BETA BATTERIES

In the electrochemistry of sodium beta (Na-beta) batteries, sodium is exchanged between the electrodes while charging and discharging having the operating temperature above the melting point of sodium (nearly 350°C). They use the thick tubular beta-alumina ($\beta''\text{-Al}_2\text{O}_3$) membrane as electrolyte which transfers the Na^+ ions and also acts as electric isolation between electrodes [118]. Sodium-sulfur (Na-S) and sodium-metal halide are the two broad classifications made in the Na-beta batteries based on the type of cathode material. In Na-S batteries molten Sulphur in liquid state is used as cathode and liquid state solid sodium in molten form as anode separated by non-aqueous beta alumina ceramic acting as both electrolyte and isolator. As shown in Fig. 14 the interface of sodium (Na) and beta alumina produce the Na^+ ions by oxidation of the molten sodium, the Na^+ ions passes through the solid electrolyte and recombines with Sulphur at anode in discharging process and forming disodium pentasulfide (Na_2S_5), which can be reversed during the charging process [119].

The electrochemical reactions are given as:



Overall chemical reaction is:



At the high operating temperatures of 270 to 350°C the formation of disodium pentasulfide (Na_2S_5) leads to two-phase liquid mixture as it remains immiscible from the Sulphur up to half of the discharge in cell whose open circuit voltage will be 2.08 V, if Na content falls below the Na_2S_5

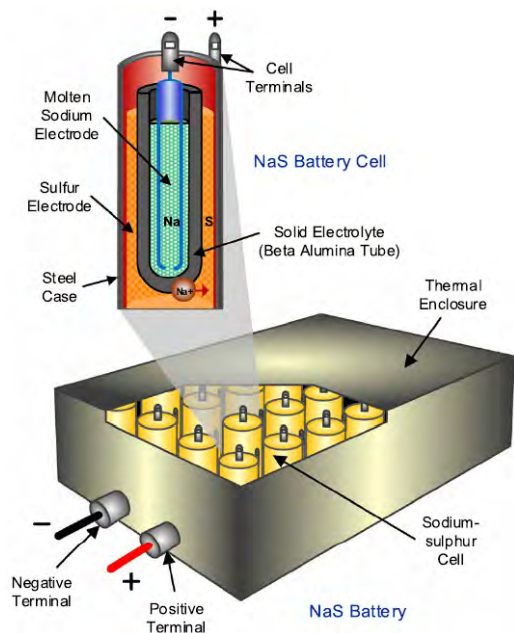
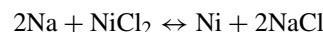


FIGURE 15. Tubular configuration design of Na-beta battery cells [46].

then single phase sodium polysulfide is formed with higher content of sulfur, which will be deposited on the electrolyte if not managed properly. During charging the Na_2S_5 will be oxidized and the chemical reactions will be reversed as discussed above [119], [120]. They are manufactured in the tubular design as shown in Fig. 15, to incorporate the volumetric changes during cycling and minimizing sealing material required [95]. The Na-S batteries have long lifetime (~ 15 years), good energy densities (150-300 Wh/L), almost zero self-discharge rate (0.05% to 1%), high energy efficient (75-90%) and full life cycles typically ~ 5000 [10]. The recyclability is also high ($\sim 99\%$) due to the inexpensive and non-toxic nature of the battery materials. Therefore, it is best suited and efficient option for the high power energy management system stationary applications such as: load levelling, peak shaving, minimization of voltage sag and smooth integration of renewable energy resources [86]. Nonetheless, Na-S system suffers from high internal resistance, highly corrosive nature of molten cathodes and high operating temperature; which requires cost effective materials for the cells, especially the sealing of cells which can withstand the 350°C temperature without allowing any vapor and direct contact with highly reactive electrode materials. Any fracture in the electrolyte ceramic will bring the both molten high temperature electrodes in direct contact, causing the flames and explosion [120]. During the discharging the exothermic reactions maintain the internal temperature of cell while in charging mode (i.e. endothermic reaction takes place), hence a thermal management system is needed to indorse the high temperature for good conductivity of beta-alumina. This mechanism will leads to the increase in the cost of the Na-S system [113].

Sodium-metal halide (Na-MeCl₂) batteries as also known as zero emission battery research activity (ZEBRA). They have most suitable features for EV applications due to their high energy density, tolerance towards over charging/discharging, more safe characteristics along with increased cell voltage (~ 2.58 V), less corrosive, long life cycle and economical than Na-S batteries [121]. Even from construction point of view they are similar to Na-S batteries, the major difference is usage of semisolid porous active metal chloride (MeCl₂) at cathode instead of sulfur together with the secondary electrolyte of molten sodium aluminum tetra chloride (NaAlCl_4). The metal chloride can be NiCl_2 , FeCl_2 or Ni-FeCl_2 , thus the cell operating temperature is decreased to 270°C along with increased pulse power capacity. During discharge the Na^+ ions from electrolyte interface are transferred to cathode through the beta-alumina and though the molten NaAlCl_4 . As a result of electrochemical process, the MeCl_2 is transferred into the salt (NaCl) and parent metal Me [122]. The process is reversible during charging with oxidization of Me metal. The SoC is determined by the accumulation of NaCl at cathode. The overall chemical reaction of the nickel chloride (NiCl_2) is give as:



They are typically employed in the large and medium power (> 20 kWh) applications of EVs, hybrid EVs, electric traction and fleet ships where high energy density is required [123]. They have easier solutions for low resistance potential failures, corrosion and sealing exchange than that of Na-S. The major setback of ZEBRA batteries is its high as it is manufactured by only limited companies around the globe. Similar to that of Na-S type they also require dedicated thermal management system, when not in use nearly 14% of its own capacity per day is consumed to maintain the 270°C operating temperature [123]. The state of charge is limited to 80% with 1C current per cell and voltage of 2.58 V in order to protect it from cell damage and chemical degradation when it is undergoing the fast charging which is desirable for EVs and hybrid vehicles [124]. Under high depth of discharge the power density of ZEBRA battery is maintained by adding the iron to the positive electrode material, which provides the capacity to withstand the short span high discharge at any DoD [124].

4) METAL-AIR BATTERIES

Metal-air batteries have high theoretical energy densities in order of 1300–1100 Wh/kg higher than the current Li-ion theoretical energy density of 450 Wh/kg [125]. As shown in Table 5, they consist of pure metals (Ca, Mg, Fe, Al, Li and Zn) as anode and inexhaustible air supply is provided by open cell structure to use oxygen as cathode [126]. They form oxides/peroxides after reduction reaction from atmospheric oxygen. Basically, metal-air batteries are classified into two groups: one is aqueous electrolyte cells which are insensitive to moisture and second group is based on aprotic solvent electrolyte, which will be damaged by moisture

TABLE 5. Energy densities of different metal air batteries [129].

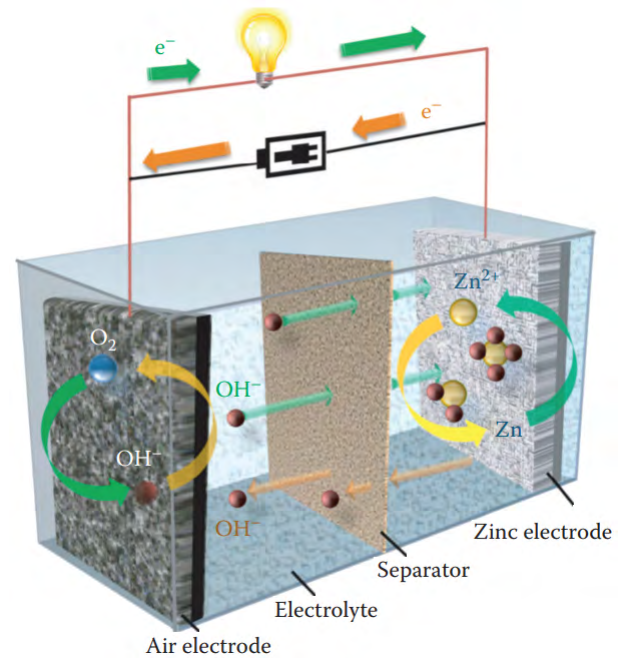
| Metal Oxygen | Open Circuit Potential (Volts) | Energy Density (Wh/kg) | Energy Density (Wh/L) | Remarks |
|--------------|--------------------------------|------------------------|-----------------------|-----------|
| Al-air | 2.71 | 4116 | 14100 | Primary |
| Ca-air | 3.10 | 2980 | 9960 | No Report |
| Mg-air | 3.08 | 3991 | 12200 | Primary |
| Fe-air | 1.35 | 763 | 1431 | Secondary |
| Li-air | 2.96 | 3458 | 6102 | Secondary |
| Zn-air | 1.68 | 1054 | 5960 | Secondary |

content [127]. Calcium-air (Ca-air) batteries are very expensive and their capacity will also degrade gradually. So, in order to increase efficiency, Ca is used as metal alloy in electrodes. Magnesium-air (Mg-air) batteries have high theoretical voltage (3.10 V), low cost, light weight, harmless and available in both land and sea water. It is mostly preferred in undersea vehicle applications, nevertheless problems of high self-discharge and heat generation limited them [127]. Iron-air (Fe-air) batteries have low practical specific energy of around 760 Wh/kg, it offers low cost and prolonged electrical life cycles. Furthermore, it can be used with combination of fuel cells, where the hydrogen formed during oxidation of iron will be consumed by the fuel cell and in reverse operation of fuel cell, the generated hydrogen is used for reduction of iron oxide to metallic iron [128].

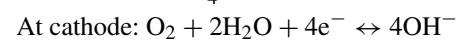
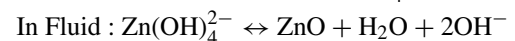
Aluminum air (Al-air) batteries have very high theoretical specific energy 4116 Wh/kg and terminal voltage (2.71 as shown in Table 5, it can go up to 2.75 V in case of Al_2O_3). They are also economical if the reaction product is recycled. Fuel efficiency in case of Al-air EVs is around 15% when compared with internal combustion engine. The major limitation of this technology is infeasibility of electrical recharge and aluminum needs to be replaced mechanically after every discharge. Due to cell irreversibility and high self-discharge rate, the Al-air batteries generate heat and cause in loss of water, which results in runaway conditions [127].

Lithium-air (Li-air) battery has high theoretical specific energy of 11140 Wh/kg (excluding air), nearly 100 times more than other batteries, whereas petrol has 10150 Wh/kg specific energy [128]. The practical values are less than half of that, around 3500 Wh/kg as shown in Table 5. Nevertheless, safety risk of flames due to high reactivity of Li with air and humidity limited its applications [130].

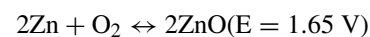
At present only, the Zinc-air (Zn-air) batteries are most attractive and technically feasible among the various metal-air chemistries available [91]. Their theoretical specific energy is 1350 Wh/kg, and practical energy density of 1054 Wh/kg, the basic model of Zn-air battery has three parts: anode made up of zinc metal, a separator and air as cathode electrode as shown in the Fig. 16. It has combined properties of FC and conventional batteries along with feasibility of electrically and mechanically rechargeable without any shape deformation [131]. While discharging, the electrons are liberated through the electrochemical reaction of the zinc anode and air cathode in presence of the electrolyte,

**FIGURE 16.** Zinc-air battery schematic representation [129].

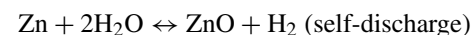
an oxygen reduction reaction takes place at the cathode resulting in the formation of hydroxide ions. These hydroxide ions migrate from anode to cathode and forms the insoluble zinc oxide (ZnO). During charging, the reversible redox reaction takes place at the electrode-electrolyte interface which stores the electrical energy in the Zn-air battery [132]. The overall chemical reactions inside the Zn-air battery are given below.



The overall chemical reaction:



The columbic efficiency of the zinc electrode is affected by the self-discharge due to the parasitic corrosion and thermodynamic instability of zinc in aqueous electrolyte. The hydrogen gas is formed as a result of self-discharge [129], [131].



The rate of reaction of Zn-air battery will be controlled by the flow of air, in order to increase the life cycle, some of the advanced systems have bi-functional air electrodes. Designing of the rechargeable Zn-air battery is a complex procedure involving closely controlled zinc precipitation from water based electrolyte [131]. Zn-air batteries are classified into three types based on EV application: (i) primary onboard battery pack, (ii) mechanically replaced zinc electrode secondary batteries, (iii) secondary batteries of hydraulic refueled electrolyte/zinc slurry. Nevertheless, the dendrite formation at zinc anode, non-uniform dissolution of

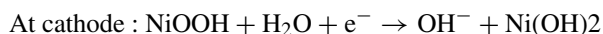
zinc, higher charge overpotential than discharge overpotential and designing of bi-functional air cathode limited its marketability [131], [133].

5) OTHER COMMONLY USED BATTARIES

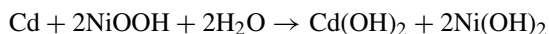
Nickel based batteries are one the oldest battery technologies which are in development since 1990s. They are employed in wide range of applications from uninterrupted power supplies (UPS), telecommunication devices and electronic equipment [134]. In nickel batteries the anode is active material comprising nickel oxyhydroxide, electrolyte will be potassium hydroxide and any one metal (such as: Cd/MH/Fe/Zn or H₂) as cathode. Among them nickel cadmium (Ni-Cd) and nickel metal hydride (Ni-MH) are more common and commercialized. Whereas nickel iron (Ni-Fe), nickel hydrogen (Ni-H₂) and nickel zinc (Ni-Zn) batteries are less common for specific applications only [46]. Due to low specific energy, high maintenance, less lifecycles and high cost, the Ni-Fe and Ni-Zn have limited applications with only 75% energy efficiency.

Whereas Ni-H₂ has high over charging or over discharging tolerance, long lifecycles and large ratings but they are very expensive, suffers with self-discharge and low volumetric energy density due to release of H₂. They are specially designed for space and aircraft applications [133]. Ni-Cd are most successful battery products with technical advantages of large number of lifecycles (2000–2500), nominal cell voltage of 1.2 V, self-discharge rate at 10% per month, efficiency of 70-90% and energy density of 40-60 Wh/kg. They are capable to operate at extreme temperatures of –20° to –40°C. In Ni-Cd, anode is nickel hydroxide (Ni(OH)₂), cadmium metal as cathode and electrolyte is aqueous solution of potassium hydroxide (KOH) [133].

The electrochemical discharging reactions of nickel-based batteries are given as:



The overall chemical reaction:



Ni-Cd batteries are reliable and does not require much maintenance. The DoD decides the number of lifecycles, in advanced designs with only 10% DoD the lifecycles will reach to 50,000 [135]. Nevertheless, the major disadvantage is the toxic heavy nature of the cadmium and nickel, causing environmental hazards. They have been prohibited for consumer use and limited to only stationary applications by many European countries [136]. Also they are nearly 10 times costlier than the lead-acid batteries besides of having memory effect [137]. Due to memory effect the maximum capacity of the battery and rated output voltage will get decreased drastically if the battery is subjected to repeated charging with only low DoD, it is also called as “voltage depression effect” [137]. Hence, they are not been commercially successful for utility scale EES applications.

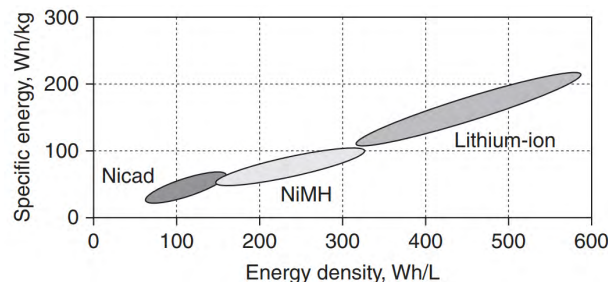


FIGURE 17. Storage capacities of Nickel and Li-ion batteries [133].

Ni-MH batteries have very high nominal capacity of an equivalent Ni-Cd and lead-acid batteries as compared in the Fig. 17. They are initially developed to replace the Ni-Cd batteries, having all positive properties of Ni-Cd along with less memory effect, wide operating temperature and negligible environmental impacts [91]. The chemical composition is almost similar to Ni-Cd except the hydrogen ion negative electrode plate in Ni-MH which gives the technical features such as: specific energy of 60–120 Wh/kg, increased lifecycles (~3000) with 70-90% efficiency and very low internal resistance. Due to which they are suitable for many sensitive electronic devices [138]. Also for applications of hybrid EVs, portable and mobile devices the sealed Ni-MH batteries are attractive due to robust and safer characteristics compared with Li-ion batteries [138], [139]. The limitations of Ni-MH are: high self-discharge rate (5-30% per month), sensitive to overcharging and DoD, time dependent nature and rapid lifecycle degradation. The cost will increase further, if, timer based or smart chargers are employed for avoiding the overcharging or DoD of NiMH batteries [138], [140].

6) EXTERNAL STORAGE BES SYSTEMS (FLOW BATTERIES)

Flow batteries are advanced aqueous electrolyte energy storage systems having advantage of operating near to ambient temperature [133]. Unlike the conventional secondary batteries where the electrodes of active material will participate in energy conversion, in flow batteries the energy is stored in active electrolytes of two separate external tanks (reservoirs), hence no self-discharge. An electrochemical cell will pump the electrolytes into the reactor comprising of battery cells stack where the chemical energy converted into electrical energy and vice-versa as shown in the Fig. 18. For production of electricity, a microscopic membrane will separate the both electrolytes and permits only limited ions to cross through inside the reactor of cell which will participate in reduction and oxidation (Redox) reactions [141]. Flow batteries are fully reversible by applying the DC voltage to electrodes while charging the battery. The most attractive feature of flow batteries is the decoupling between power rating and total energy storage of battery. The power rating of flow battery depends upon the size of electrodes and number of cells in the stack whereas the auxiliary volume of the reservoirs (size of tank) and concentration of electrolyte is directly

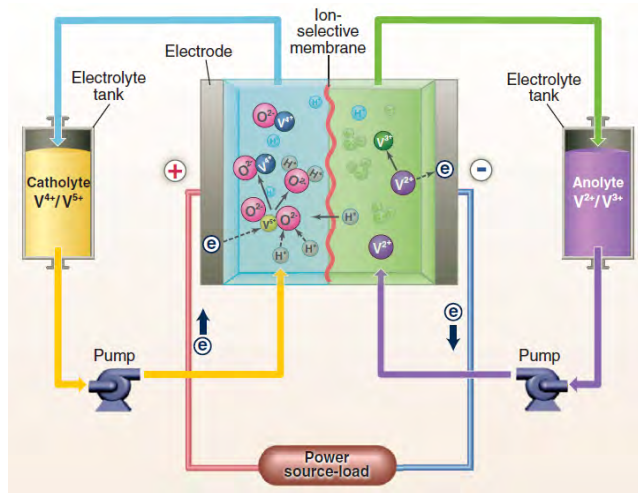


FIGURE 18. Redox flow (vanadium) batteries [120].

TABLE 6. Features of various electrochemical storage technologies [143].

| ESS Type | Energy Density (Wh/kg) | Discharge Time (H) | Response Time | Round-Trip Efficiency | Life Cycles |
|-----------|------------------------|--------------------|---------------|-----------------------|-------------|
| Lead-acid | 25-50 | 1-2 | ms | 75% | 800 |
| Na-S | 150-120 | 2-6 | ms | 89% | 4500 |
| Na-Ni-Cl | 95-120 | 0.5-2 | ms | 90% | 4500 |
| Li-ion | 200-300 | 1 | ms | 87% | 4000 |
| FCs | 800-1300 | >10 | ms | 24% | 300 |
| VRFB | 25-30 | >10 | ms | 75% | 20000 |

proportional to the energy storage capacity of battery. Hence, they are favorable for both energy and power related storage applications [141], [142].

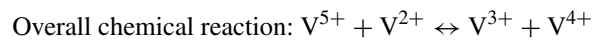
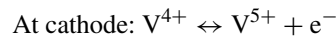
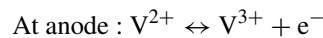
In many features, flow batteries are similar to FCs (also have independent power and energy ratings) nevertheless FCs are not reversible beside low round trip efficiency, uneconomical and short lifecycles as compared in the Table 6 [92]. Hence, flow batteries are emerging as a promising option for the wide range of stationary applications. Long discharge times can be achieved in case of flow batteries due to power and energy independent sizing of system. Other advantages of flow batteries include: capable of high overloading for short times, response time in milli seconds, low self-discharge in sealed storage tanks, room temperature operation, long charge and discharge lifecycles and high round trip efficiency [143].

Depending on the electroactive components of electrolyte the flow batteries are classified into redox flow batteries and hybrid flow batteries [83].

a: REDOX FLOW BATTERIES

Vanadium redox flow batteries (VRFB) are the one of most mature flow battery technologies. In VRFB one common electrolyte (such as vanadium sulphate dissolved in

(H₂SO₄) sulfuric acid) is used to store the energy in charged ions of different valance states, avoiding the two half-cell electrolytes from cross contamination [144]. During the charging/discharging process the H⁺ ions will be exchanged between the vanadium redox couples of bivalent/trivalent (V²⁺/ V³⁺) in the anolyte tank and tetravalent/pentavalent (V⁴⁺/ V⁵⁺) in the catholyte tank as shown in the Fig. 18 [145]. The ionic concentration of 1.5 –2 M is maintained in the 2-5 M concentrated sulfuric acid solution. The electrodes of VRFB cell stack are uniquely designed to increase the hydrophilicity and catalytic effects which are made up of carbon or graphite felts. If cationic membrane is used the H⁺ ions will migrate through polymer membrane, else bisulfate (HSO₄⁻) ions will migrate if the membrane is of anion [146]. The electrochemical half-cell reactions of VRFB are:



The VRFB have very low parasitic losses and number of lifecycles are usually above 10000. The standard open circuit potential of individual cell is about 1.259 V at 25° C and performs at nearly 90% efficiency in light load conditions [146]. Constant voltage at all charges, operating temperature of 10-40° C and instant recharging capacity by electrolyte swap are the other major advantages of VRFB [141], [147]. VRFBs are commercialized in wide range of stationary applications with power ratings form kW to MW in power quality enhancement, UPS, load levelling and in integration and support of intermittent nature of renewable energy resources [141], [145], [148]. Nevertheless major challenges of VRFB includes costly electrolyte materials, energy density is limited (25-30 Wh/kg) because of precipitation of solid vanadium compounds if the concentration exceeds over 2 M above 40° C or below 10° C which is very less compared to other technologies for EVs as shown in Table 6, handling chemical solutions with potential of leakage, pumping and shunt current losses also accounts to decrease the round trip efficiency of system [143], [144].

b: HYBRID FLOW BATTERIES

Hybrid flow batteries (HFB) are the combination of the secondary batteries and flow batteries. Here, one of the is stored inside the electrochemical cell and other active material will be liquid electrolyte stored in the external reservoir. The capacity of HFB depends upon the size of electrochemical cell. In HFB at least one of the redox couples have deposition of solid or gaseous species during charging/discharging process [10]. Zinc bromine flow battery (ZBB) is the widely known example in zinc halogen redox flow battery systems. Zinc is distinctive negative electrode widely employed in electrochemical cells by reason of negative potential in both acidic (-0.76) and alkaline (-1.22) aqueous medium [141]. The Zn⁺² ions will

be deposited at the electrode during charging and while discharging the ions will flows back into the acidic solution of ZBB electrolyte. They have high theoretical potential of 1.85 V, relative high energy density (35-75 Wh/L), operating temperature range of (20°–50° C), lifecycles of 10–20 years, large discharge durations (8–10 hours) and large DoD capability [133]. The development of ZBB is hindered by the problems of zinc corrosion, toxic nature of the bromine, formation of zinc dendrite and hydrogen gas, high self-discharge rates due to the migration of bromine ions into the zinc electrode and lower round-trip efficiencies (65–75%). Polarization owing to uneven reactions of Zn/Zn²⁺ couple in comparison to Br₂/Br – couple will lead the battery failure in case of ZBB [143], [146], [149]. To overcome these limitations polysulfide bromine flow batteries are developed, which are cost effective due to the advantage of easily available and highly soluble aqueous electrolyte solutions [150]. More recently, lithium flow batteries have been introduced with technical specifications of 3.8 V discharge cell voltage and energy density of 397 Wh/m³ in electrolyte volume. Hence, the increased active material concentration (<5 M) has resulted in energy densities to 10 times of that of VRFB with 98% round trip columbic efficiency and 88% energy efficiency. Which are attractive for EV applications, nevertheless they are still in developing stage [151].

F. HYBRID ENERGY STORAGE SYSTEMS (HESS)

HESS is the process of creating a super device together with complementary characteristics of two or more heterogeneous storage systems together. Coping with harsh working environment of real time applications, a single ESS system cannot meet all the desirable technicalities (such as: energy density, power rating, operating temperature, discharge rate, life cycle and cost) [152]. In HESS a near optimal performance with improved cycle efficiency can be achieved by synergizing the individual advantages of each unique ESS [153]. As shown in the Table 7, the main aim of all the HESS systems is combining high energy density (normally slow response systems) with high power density (fast response systems) devices in order to achieve fast responding high energy and high power rating characteristics [154].

From the above classification it is noted that battery systems can be employed in both high power or high energy region due to their diverse and unique capabilities [155]. In the HESS system the organization of heterogeneous systems will be in such manner that, short term high power needs will be supplied by high power devices while long term energy requirements will be met by high energy devices [156]. Different heterogeneous energy storage combinations are listed in Table 8, some of them are feasible and mature while other combinations suffers from limitations. The size and possible combination of HESS system depends on factors of environment, economy and type of usage [53].

In order to overcome the difficulties of expensive DC-DC converters and low efficiency problem, advanced hybrid capacitor architectures have been proposed. Unlike

TABLE 7. Classification of high power and high energy systems [157].

| <i>High Power Devices (Fast Response)</i> | <i>High Energy Devices (Slow Response)</i> |
|---|--|
| FES | PHS |
| SCES | CAES |
| SMES | FC |
| BES | BES |

TABLE 8. Theoretically possible HESS combinations.

| High Energy Supplier | High Power Supplier |
|----------------------|---------------------|
| PHS [158][159][160] | SMES |
| | SCES |
| | FES |
| | BES |
| CAES [161][162][30] | SMES |
| | SCES |
| | FES |
| | BES |
| FC [163][164][165] | SMES |
| | SCES |
| | FES |
| | BES |
| BES [60][166][167] | SMES |
| | SCES |
| | FES |

electric double layer symmetric capacitors, hybrid capacitors have optimally balanced mass of two different electrochemical windows for two different electrodes, having unique capacitances [168]. They combine the features of faradic (battery type) devices and non-faradic (capacitor type) devices, with increased overall cell potential, higher energy and power densities. The reported specific energy of hybrid capacitors is about 35 Wh/kg with power densities around 10000 W/kg [169], [170]. In addition, the operating temperature of hybrid capacitors is possible from –50° C to +200° C and frequency response of 5 KHz. Applications of hybrid capacitors include automotive and transportation sector, regenerative braking, power system stabilization, catalyst preheating, distribution sector and consumer electronics [171]. Among various combinations of positive and negative electrode materials, Li-ion hybrid capacitors sense to be more attractive option in bridging the gap between Li-ion batteries (high energy density devices) and EDLC (high power density devices) [172]. Porous activated high area carbon material prepared from carbonized precursor is used as positive electrode and significantly doped Li-ion carbon material is used as negative electrode [169], [172].

A sandwiched structure stacking hybrid capacitor cell (cathode-separator-anode) along with lithium metal foil will be inserted into an aluminum plastic bag after adding liquid Li-ion salt electrolyte as shown in Fig. 19. Lithium metal foil will be used as counter electrode for accomplishing pre-doping of the hard carbon anode electrode through electrochemical discharge process (lithium intercalation) [173]. Besides that, high capacity retention rate (≥98% of its initial capacity) with 100% columbic efficiency remains stable

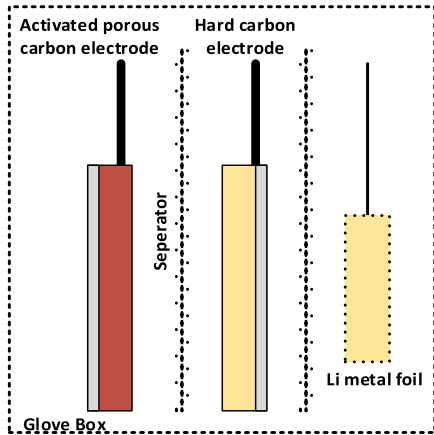


FIGURE 19. Schematic construction of hybrid Li-ion capacitors.

nearly over 2000 electrochemical cycles for hybrid capacitors [173]. However, complications of the varying voltage will arise due to critical process of pre-doping, high rate metal plating and formation of solid electrolyte interphase layer [174]. An alternate economic and easily accessible model of sodium-ion (Na-ion) hybrid capacitors is discussed in [175]. Features of Na-ion capacitors include 140 Wh/kg at 630 W/kg (normally), 103 kW/kg ultra-power density at 43 Wh/kg (within 1.5 sec) and stable capacity attenuation over 10000 cycles. Nevertheless, still research is needed in order to overcome the limitations of Na-ion hybrid capacitors availability in commercial market [175].

A generalized HESS architecture is shown in Fig. 20, designed to ensure to scalability, modularity and flexibility for the hybrid system [176]. Where a charge transfer interconnects (CTI) medium will interconnect the multiple heterogeneous ESS systems to each other. Each ESS bank consists of multiple homogeneous ESS elements supported by a bidirectional converter for typical voltage matching of CTI while charging and discharging. Various power sources and load devices (AC or DC type) are get connected to HESS through unidirectional power converters and CTI as shown in the architecture. Based on the topologies of CTI interconnections, the HESS system can be classified as passive topology (parallel connection of ESS banks), active topology (decoupled connection of ESS banks according to their characteristics) and discrete topology (reconfigurable adaptive switching topology based on requirements of source and load) [177], [178]. The system controller and charge management policies are the microgrid tools to optimize and control the mode of operation, connections, voltage and currents while charging/discharging through charge replacement of CTI [179]. The status of each ESS bank (such as: SoC and DoD) will be controlled and monitored at each time instant to get the best performance of the HESS [180]. A Wind-HESS topology is shown in the Fig. 21. As shown, it consists of wind farm, CAES system, FES system, surplus energy storage system, thermal storage (heat oil tank and cold oil tank) and load module.

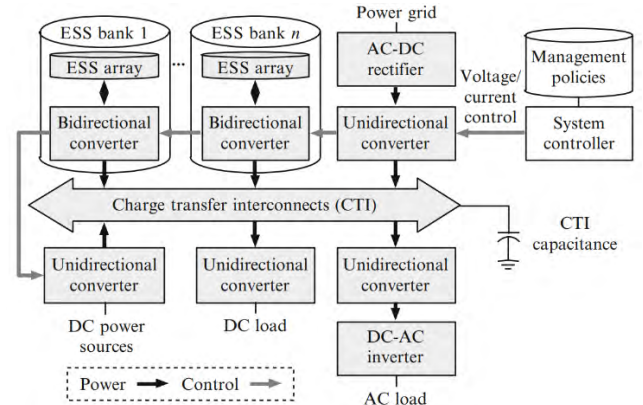


FIGURE 20. Generalized architecture of HESS [176].

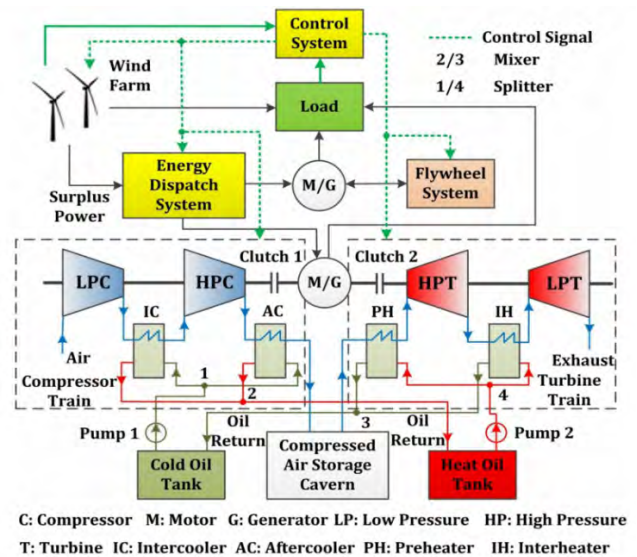


FIGURE 21. Wind-Hybrid ESS developed in [162].

After meeting the load requirements in the microgrid the surplus energy generated by the wind farm will be utilized to store the energy in the form of electrical energy (energy dispatch system), kinetic energy (flywheel system), mechanical energy (CAES cavern) and thermal energy of oil tanks. During the peak load or wind deficit times, the stored energy will be used to meet the electricity gap through the optimal control of each storage system with respect to their SoC, DoD, speed of discharge, energy and power ratings [162]. Hence, the use of multifunctional HESS will be the optimum option in future, which requires an interdisciplinary collaboration and research for further development and progress in this field [152].

G. SMART / INNOVATIVE TECHNOLOGIES

1) BIOLOGICALLY AND MICROORGANISM INSPIRED FUEL CELLS

Microbial fuel cell (MFC) takes the advantage of microbial metabolism and solid electron acceptor to convert the

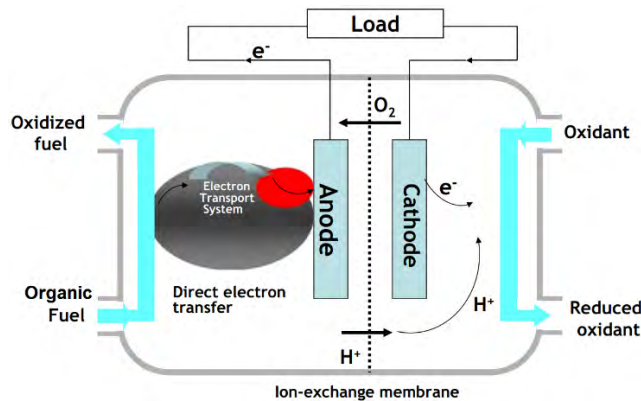


FIGURE 22. Electricity generation from organic wastes by MFC.

chemical energy of waste into electricity as like bio-electrochemical systems [181]. MFC operates similar to chemical FC, nevertheless the microorganisms of biodegradable waste (also known as exoelectrogens) will oxidize at anode and donate electrons in MFC. As shown in Fig. 22 the terminal acceptor (most commonly O_2) molecule at cathode will be reduced by the electrons flown from external load circuit [182]. Wide range of low-grade wastes such as: domestic wastewater, food wastes, landfill leachate, industrial wastes, sewage sludge, animal wastes and plant wastes can be used to produce electricity in MFC, however FC is limited to certain chemicals only [181]. Also, the MFC is safer and more reliable due to working at ambient temperature and neutral pH value unlike chemical FC where additional arrangements are needed due to operating temperature of 500-1000 °C and for storing acidic and alkaline materials.

Direct chemical energy conversion into electricity is another potential advantage of MFC over anaerobic digestion (bio gas combustion), where 65% energy will be lost during multi-step energy conversion. Besides that the CO_2 liberated from MFC is environmentally neutral and do not contribute for global warming [183]. Nevertheless, the non-linear nature of the MFC is a major limitation to get large power production, which is possible in chemical FCs through series and parallel connections. Thermodynamic limitations and high internal energy loss are also reasons for low power rating (typically 200 W/L) of MFC [184]. The construction of MFC can be mediator based or mediator free depending on requirement. Methyl blue or humic acid mediator are used to accelerate the electron transfers to electrode during cell reaction, whereas in mediator free MFC electrochemically active bacteria are used to transfer the electrons to electrode. The applications of MFC include waste water treatment, hydrogen generation, low power electronic and medical applications [181], [185].

2) SOLAR FUELS

Solar fuels can be efficient, durable, environment friendly and cost-effective option of energy storage. Presently they are at early stage of development with latest scientific

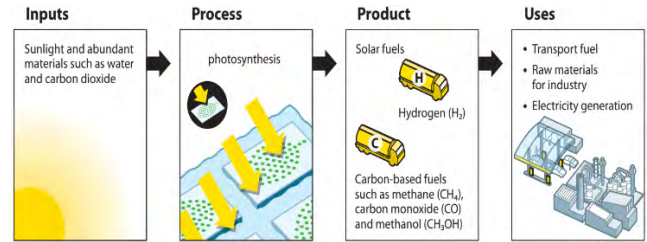


FIGURE 23. Pathway of photosynthesis in solar fuels.

breakthroughs to harvest sunlight energy and produce fuels which can be utilized to produce electricity [186]. Solar fuels capture the radiative energy of sunlight through parabolic mirrors in chemical bonds of material and these fuels can be transported or stored for electricity generation [187]. The storage duration can be from few hours to few months long with potential of 20 MW power rating and specific energy in range of (800–100,000 Wh/kg) [43], [96]. Solar fuels are “100% virtual storage efficiency” systems because of storage is integral part of energy cycle unlike the intermediate components which results in energy loss. Which is the major lead fuels where the change in conversion efficiency with and without storage will be close to zero [188].

Photosynthesis is the blue print sophisticated system in nature through which plants, algae and some types of bacteria absorbs the suns radiation and produce the oxygen and carbohydrates from the CO_2 and water. The produced carbohydrates (sugars and starches) will be treated as fuel in solar fuel cell technology as shown in Fig. 23, which includes three main approaches: natural photosynthesis, artificial photosynthesis and thermochemical approach [186]. The fuels which are produced during photosynthesis are hydrogen (H_2), carbon-based fuels (CH_4 , CO and CH_3OH) and solar chemical heat pipe. While the natural photosynthesis is chlorophyll based conversion, whereas artificial photosynthesis relies upon water splitting catalysts (e.g., ruthenium and rhenium) to capture the sunlight and convert the water and CO_2 into oxygen and other materials [187]. Thermochemical approach depends upon strong sunlight radiant energy at very high temperature in a closed environment to carry out endothermic process and splitting the water into its constituent parts to produce hydrogen and other materials [189]. Substantial advances and research is going on to utilize the abundant potential of solar energy as a cost effective option for utility scale applications in near future [190].

3) GRAPHITE SOLAR STORAGE

Graphite is a stable form of carbon under standard conditions and is considered as highest grade of coal also known as meta-anthracite having potential of fueling future clean energy. The idea is to collect and store the solar heat energy in graphite blocks that can be utilized for electricity generation through steam Rankine cycle or other heat engine cycles [191]. As shown in Fig. 24 the graphite is an ideal medium to store energy due to very high melting point (3500 °C) and

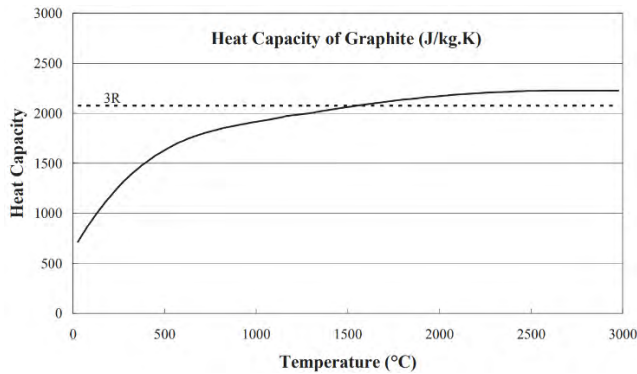


FIGURE 24. Heat capacity of graphite with respect to temperature [195].

high specific heat capacity (ability to store the heat energy) ranging from 300 kWh/ton at 750 °C to 1000 kWh/ton at 1800 °C [192]. They will be very advantageous when integrated with concentrating solar power technologies, one such installation is planned in Queensland project of Australia where graphite cubes are elevated to be pointed by mirrors to collect the solar heat [193]. The blocks are heated up to 1800 °C temperature, able to produce steam for turbines on demand. Another hybrid graphite solar storage power project was developed by “Larkden Pty Ltd” in Cooma, Australia [194].

Where a large graphite thermal battery is demonstrated to store the solar heat and a heat exchanging regulator for the recovery and control of thermal energy from the graphite. For a 50 MW plant using graphite thermal battery, the per kWh energy will be approximately 80% less costlier than electrical battery technology [194]. Graphite solar systems can be covered to avoid dust and still they collect the energy from ambient air, unlike the conventional PV systems where efficiency will be relative to direct sunlight and dust installation [196]. Other major advantages of graphite over chemical batteries are: low cost, chemically inert, resistant to corrosion, strong and stable at high temperatures, very difficult to ignite (flame retardant) and high electrical and thermal conductivity [191]. For achieving the fast charging and long lasting EV batteries require efficient heat dissipate mechanism, graphite can be used as heat spreading material (act as black ice) for thermal management in EVs [197].

4) PAPER BATTERIES

Paper batteries are ultrathin, flexible and light weighted devices which can be used as batteries as well as capacitor. They are formed by combination of nano sized composite paper (90% of cellulose) and carbon nanotubes [198]. Paper batteries have potential to provide both short term and long-term steady power production and energy bursts (if required) for next generation electronic, medical devices and hybrid vehicles. They can be operated in temperature range of -77 to 100 °C and have thinness of 0.5–0.025 mm (less than a printer paper) which can be used as folded, twisted, molded, crumpled, shaped and cut in variety of applications without

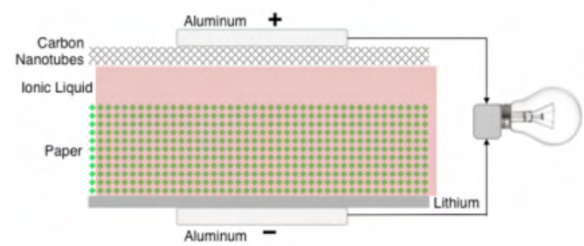


FIGURE 25. Model design of paper battery.

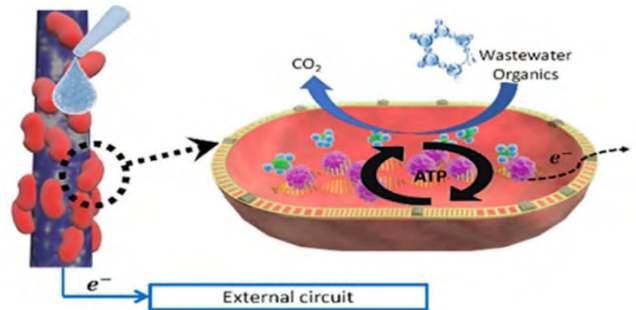


FIGURE 26. Schematic illustration of power generation in paper based MFC [201].

energy loss [199]. The nano composite paper combines the feature of super capacitor (high energy density) and battery (high energy storage capacity) able to produce the bursts of extreme power on demand [198]. Among the different ways to construct a paper battery the most efficient and simple one is shown in Fig. 25.

An ordinary cellulose paper will be coated with ionic solution at one side of paper surface and specially prepared carbon nanotube ink will be spread on ionic surface which will act as cathode. Now, the other side of paper will be laminated with a very thin layer of lithium acts as anode. Join the two surfaces with aluminum electrodes to flow the electricity generated from chemical reactions between electrolyte-carbon and electrolyte-metal through the load circuit [200]. The potential generated will be close to 1.5 V which can be modified by stacking different paper batteries one over the other. These are biodegradable, non-toxic, durable, very light weight, leakage proof and easily recyclable. Nevertheless they are harmful for lungs if inhaled, generates e-waste and will be uneconomical for high power ratings [200]. Another paper based MFC battery systems are developed which uses bacteria for power generation [201]. As shown in Fig. 26 the “exoelectrogens” are special type of bacteria which can transfer the electrons outside of their cells while they are generating the energy for themselves. The electron flow is used to power the battery which can be activated by just adding a water or liquid on to it [202].

Among all the paper-based batteries, paper based MFCs are low cost, easy fabrication, self-sustainable, self-assembling and ecofriendly. However, due to the disadvantages of low performance (caused by soaking of electrons by

TABLE 9. Technical and economical specifications of various ESS technologies – I.

| ESS technology | Power range (MW) | Energy rating (kWh) | Energy density (Wh/kg) | Power density (W/kg) | Discharge time (ms-h) | Response time (ms-h) | Round trip efficiency (%) | References |
|---|------------------|---------------------------------------|------------------------|----------------------|-----------------------|----------------------|---------------------------|-------------------------------|
| Mechanical Energy Storage Systems | | | | | | | | |
| PHS | 10-5000 | 2x10 ⁵ - 5x10 ⁵ | 0.5-1.5 | — | 1 - 24+ hrs | min | 70-85 | [43][34][221][222][30] |
| FES | 0.01-0.25 | 25-5k | 5-80 | 700-12000 | sec - 15 min | sec | 90-95 | [43][135][33][44][142] |
| CAES (underground) | 5-300 | 2x10 ⁵ - 10 ⁶ | 30-60 | — | 1 - 24+ hrs | min | 41-75 | [51][99][91][99][83] |
| CAES (overground) | 3-15 | 2 - 8.3 | 140-300 bar | — | 2 - 4 hrs | sec - min | 70-90 | [142][83][142][45] |
| Electrical Energy Storage Systems | | | | | | | | |
| SCES | 0.01-0.3 | 10 ⁻³ - 5 | 0.05 - 15 | 10 - 10 ⁶ | ms - min | ms | 85 - 95 | [69][68][64][58][62] |
| SMES | 0.01-10 | 15-100, 5x10 ⁶ | 0.5 - 5 | 500 - 2k | ms - sec | ms | 90 - 97 | [70][76][222][77][223] |
| Thermal Energy Storage Systems | | | | | | | | |
| Low temp TES | 0.01-300 | — | 100-200 | 10 - 30 | 1 - 8 hrs | Slower | 30 - 50 | [83][224][43] |
| High temp TES | 1-60 | — | 80-250 | — | 1 - 24+ hrs | not rapid | 80 | [86][83][224][82] |
| Chemical Energy Storage Systems | | | | | | | | |
| Hydrogen (FC) | 0.3-50 | < 200k | 600-1.2k | 5 - 800 | sec - 24 hrs | Sec | 30 - 50 | [92][93][92][86][33][66] |
| Electrochemical Energy Storage Systems | | | | | | | | |
| Conventional Pb-A | < 20 | 18k-100k | 30-50 | 200-400 | sec - 5 hrs | ms | 70-90 | [106][105][108][225][223] |
| Ni-Cd | < 40 | 6.75k | 15-55 | 150-350 | 1 - 8 hrs | ms | 75 | [221][140][226][114][140] |
| Ni-MH | < 0.03 | 0.01-500 | 60-80 | 150-460 | hrs | ms | 70-80 | [226][140][117][108] |
| Advanced Li-ion | 0.05-100 | 250-25k | 120-230 | 150-2k | min - 1 hr | ms | 85-95 | [224][117][142][108][113][89] |
| Na-S | 10-34 | 245k | 150-240 | 150-230 | 6 - 7.2 hrs | ms | 75-90 | [222][224][108][124][117] |
| Na-MeCl ₂ (ZEBRA) | 0.005-1 | 120-5k | 86-140 | 180-245 | sec-hr | ms | 90 | [99][114][124][86][108][119] |
| Metal air Zn-air | 0.01-1 | 60-150 | 1k - 1.3k | 90-105 | 10 - 15 hrs | ms | 50 - 65 | [132][129][131][127][227] |
| Flow Battery VRFB | 0.01-10 | 4k-40k | 25 - 35 | — | 5 - 10 hrs | ms | 60-75 | [95][86][95][141][150] |
| HFB (ZBB) | 2-10 | 50-500 | 65 - 75 | — | 8 - 10 hrs | ms | 60-80 | [146][147][141][151] |

oxygen before they reach electrode) and uncertainty over its biodegradability has not translated this technology into practice and is under development [203], [204].

III. COMPARISON AND TECHNICAL ASSESMENT OF VARIOUS ESS TECHNOLOGIES

ESS will be the key component in adaptation of evolving smart grid technologies such as, demand side management, increased penetration of alternate generation and changing power delivery trends. The comprehensive analysis and investigation of ESS diversity in terms of expected technical specifications, physical constraints and ecological impact on natural resources would be required for efficient design and control of ESS. Based on that, an appropriate ESS could be selected for desired power system application [83]. Particularly, the system preferences and design parameters are measured in terms of : ESS maturity, capacity (energy density and power density), storage duration, standby time, response time, number of lifecycles, economy of storage, storage losses, conversion efficiency, thermal rating,

safety related remarks, purpose of usage, compatibility to automation, being stationary or mobile and environmental impact [205], [206]. The fulfillment of all characteristics simultaneously in single ESS would be rare possibility, consequently, based upon capacity requirement and maximum storage discharge time, we access the optimum suitable ESS technology.

The comparison of various ESS technologies based on the technical and economical characteristics is shown in the Table 9 and Table 10. Depending upon the key technical parameters of ESS technology, each of the ESS has its suitable application range, such as: energy management requires very high capacity power and energy ratings which can be met by PHS, CAES, FC, VRFB and TES. Whereas FES and SCES/SMES are more suitable for power quality improvement. The technical maturity and mass production of the particular technology will affect the capital cost needed for adaptation of ESS, Similarly the technologies such as: Na-S, ZEBRA, Ni-Cd, Ni-MH, Pb-A, li-ion, FES, SCES, SMES and TES are mature and commercially viable

TABLE 10. Technical and economical specificantions of various ESS technologies – II.

| ESS technology | Lifetime (yr) | Lifecycle (cycles) | Total capital cost | | Daily self-discharge (%) | Operating temperature (°C) | Nominal Voltage (V) | Technical maturity | References |
|---|---------------|--------------------|--------------------|--------------------|--------------------------|----------------------------|---------------------|--------------------|---------------------------|
| | | | Power cost \$/kW | Energy cost \$/kWh | | | | | |
| Mechanical Energy Storage Systems | | | | | | | | | |
| PHS | 30-60 | — | 500-2k | 5-100 | Null | Ambient | — | Mature | [224][227][33][31] |
| FES | 15-20 | 20k-100k | 100-300 | 1000-5000 | 1.3-100 | 20 to 50+ | — | Commercial | [228][224][39][135] |
| CAES (underground) | 20-40 | 8k-13k | 500-1.8k | 50-400 | ~ 0 | Ambient | — | Developed | [51][50][52][227] |
| CAES (overground) | ~ 20 | 0.5k-1.8k | 1k-1.55k | 200-250 | ~ 0 | Ambient | — | Developed | [142][229][222][45][225] |
| Electrical Energy Storage Systems | | | | | | | | | |
| SCES | 25-30 | 100k-500k | 100-300 | 300-2k | 10 - 40 | -40 to 85 | 2.3-400 | Developing | [65][68][58][62][222] |
| SMES | 20-30 | 20k – 100k | 200-350 | 1k – 10k | 10-15 | -162 to -253 | — | Demo/early | [222][76][78][77][223] |
| Thermal Energy Storage Systems | | | | | | | | | |
| Low temp TES | 10 – 40 | — | 200-300 | 20-50 | 0.5 - 1 | -12 to -150 | — | Developing | [83][224][43][86] |
| High temp TES | 5 – 15 | — | 200-300 | 30-60 | 0.05 - 1 | 400-1k | — | Demo/early | [83] [86][85] [82][43] |
| Chemical Energy Storage Systems | | | | | | | | | |
| Hydrogen (FC) | 5 - 15 | 1k – 10k | 400-2k | 1 – 15 | ~ 0 | 50-100, 600-1k | 0.2 - 1.1 | Developing/Demo | [93][92][86][230][113] |
| Electrochemical Energy Storage Systems | | | | | | | | | |
| Conventional Pb-A | 5-15 | 500-2k | 175-600 | 150-400 | 0.1 – 0.4 | -30 to 50 | 2.0-2.35 | Mature | [231][110][232][233][105] |
| Ni-Cd | 10-20 | 800-2.5k | 500-1.5k | 600-2.4k | 0.2-0.3 | -45 to 60 | 1.2 | Mature | [134][109][135][139] |
| Ni-MH | 5-10 | 800-3k | 120% of Ni-Cd | 120% of Ni-Cd | 0.4-1.2 | -20 to 45 | 1.2 | Mature | [226][231][114][99][91] |
| Advanced Li-ion | 20--25 | 1k – 10k | 1.2k-4k | 400-2.5k | 0.15-0.3 | 10 to 60, -20 to 60 | 3.6-4.2 | commercial | [114][105][233][117][234] |
| Na-S | 10-15 | 2.5k-4k | 3.2k-4k | 300-500 | 0.05-20 | 300-350 | 2.1 | commercial | [120][121][91][225] |
| Na-MeCl ₂ (ZEBRA) | 5-15 | 1k-1.2k | 150-300 | 230-345 | 15 | 270-350 | 2.58 | commercial | [120][122][121][43] |
| Metal air Zn-air | >1 | 1k - 2k | 100-250 | 60-160 | very small | 0-50 | 1.0 – 1.3 | Demo | [129][132][130][33][91] |
| Flow Battery VRFB | 10-20 | >12k | 1.4k – 3.7k | 500-800 | small | 10 - 40 | 1.4 – 1.5 | Developing | [150][141][147][146][143] |
| HFB (ZBB) | 5-10 | >2k | 1.8k – 2k | 100-700 | small | 20 - 30 | 1.82 | Developing | [141][149][150][146][86] |

for distributed grid support and installation. Nevertheless, the CAES, FC, VRFB, HFB and metal-air technologies are under development and not viable due to low efficiency and uneconomical. Among current low and medium power emerging technologies metal air batteries provides the cheapest solution to adopt, however the round-trip efficiencies of metal-air batteries, FC and TES systems are low due to high conversion losses [96].

As shown in Fig. 27 the application of the ESS technology will be classified broadly into large scale, medium scale and small scale depending upon the power rating and discharge time for suitable generation, transmission, distribution or consumer level power system application [142]. The classification and ESS suitable technology for particular storage

service and applications is covered in the Table 11. Furthermore, development is expected especially for the small scale and medium scale commercial availability of CAES, FC, FES, SCES, SMES, VRFB, HFB and Zn-air technologies for power quality, off-grid support and EV applications. New and smart environmental technologies such as: MFC, solar fuels, graphite energy storage and paper batteries are attractive options which needs the enhanced R&D to supply the power and energy requirements of various applications.

Proliferation of storage devices brings along new possibilities in power system operation and planning. In addition to static storage planning, a new field that is gaining momentum is the use of EVs for mobile storage. In other words, thanks to their ability to move around, EVs can be utilized to ferry

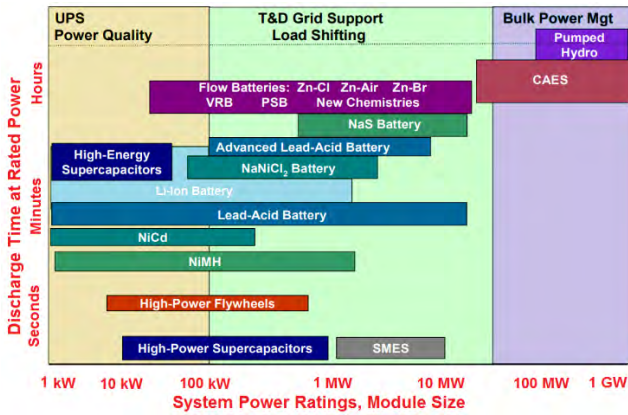


FIGURE 27. Schematic illustration of power generation in paper based MFC.

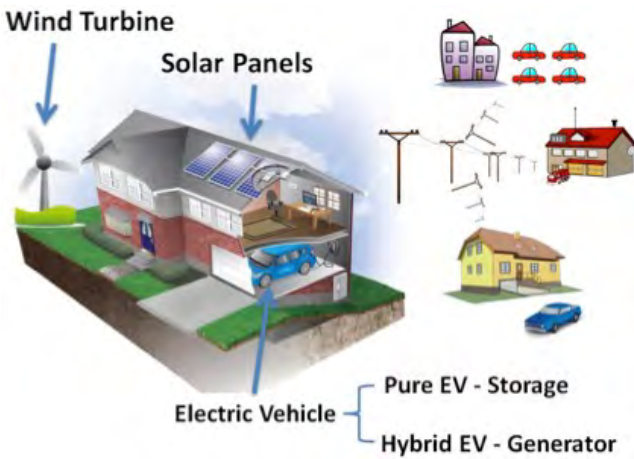


FIGURE 28. Mobile Storage with EVs for Disaster Recovery.

energy to wherever it is required. While it looks unlikely that utility companies will rely on the ability and availability of charges in EV battery, there are very viable implementation scenarios such as post-disaster recovery systems [207]. In these situations, EVs can be used as mobile storage systems to energize houses, hospitals or shelters as shown in Fig. 28. Due to the emergency condition, the cost of these solutions is not the biggest concern. The most important features for such systems are the capacity of the batteries, their discharge properties and, of course, their mobility which is unique to EVs.

It is also worthy to mention that decreasing costs made some storage types feasible to be used in first-access systems for electrification. Households which were deprived of electricity for years, got the chance to make use of stored solar energy, thanks to these PV-storage systems [208], [209]. These systems can be single solar-home systems, as shown in Fig 29. or microgrids with several generators [210]. In these systems, the cost plays a very big role due to limited purchase power, and the most important factors are price, and life-time of a storage system. There are no big charge-discharge requirements as the system load tends to be small.

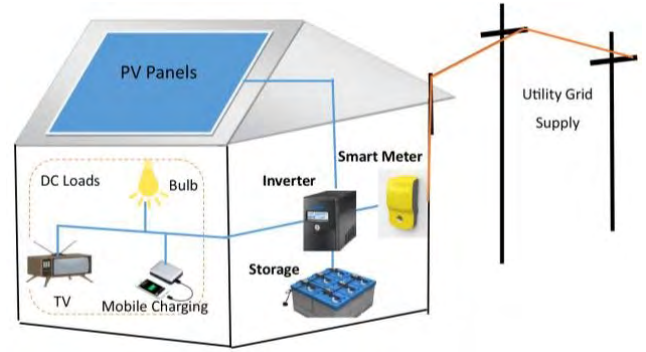


FIGURE 29. Solar Home Systems with Storage for First-Access.

However, upfront payment and the pay-back period are vital in making these systems viable [211].

IV. FUTURE RESEARCH DIRECTIONS CONSIDERING IMPACTS OF ESS IN POWER SYSTEMS FIELD

Sections above give a thorough review of the storage technologies from a construction and operational characteristics perspective. However, ESS is related to different aspects of power system operation. Therefore, the research field concerning ESS in power systems is a fertile area with many opportunities. Therefore, in this section, a snapshot of other research domains that are related to development, deployment and operation of ESS in power systems are covered.

Research spans different items from micro-level, e.g. material science to increase capacity or cost of storage technologies, to macro-level, e.g. optimal placement and sizing of utility scale ESS to increase stability. Furthermore, there is diversity in the research domains as to what aspect of ESS operation is considered. Public policy and market research focus on issues such as ownership, investment and right of use that appear together with the proliferation of ESS both at utility and residential scales. Control and communication solutions needed to manage ESS are a big part of the puzzle to solve before full benefits of Smart grid can be reaped.

Achieving a standard communication stands out in this a lot, as it holds the key to unlock many other benefits that ESS offers. All the novel optimization algorithms, transactive market mechanisms or control methods necessitate the existence of stable communication channels. These are required to monitor the current status of the power network as well as notifying new operating commands due to an optimization scheme or a market mechanism.

For standardization of data collection in power systems, a standardized information model providing syntax, semantics and structure of data communicated is required. In literature different standards have been proposed for power system data exchanges. Most of these standards are confined to any particular domain or application. The IEC 61850 standard series for power utility automation is the most promising solution since it proposes an object-oriented communication approach for all the components/domains of power system [212]. This IEC 61850 object-oriented

TABLE 11. Storage services, applications and remarks [43], [96], [116], [142], [227], [233], [235]–[238].

| Storage service | Service applications | Suitable Options | |
|----------------------------------|---|---------------------------------|--|
| | | Technology | Remarks |
| Long Duration (frequent) | <ul style="list-style-type: none"> • Load levelling • Hot reserve • Arbitrage • Bulk energy storage • Peak shaving • Frequency regulation • Intermittent seasonal balancing • Renewable penetration • Area control | PHS | Site-specific and habitat species limitation, large construction time and high capital cost |
| | | CAES (underground) | Long construction time, site-specific plant, gas required as fuel, low round trip efficiency and high capital cost |
| | | TES | Low round trip efficiency, slow response and high operational cost |
| | | VRFB / HFB | Relatively low energy density, expensive than other EcSS, toxic remains in last, electrolyte leakage protection required, too heavy, not yet proven cycle life and developing technology |
| | | FC | High cost, low efficiency, combustion of fossil fuel and developing technology |
| | | Pb-A | Too heavy weight, risk of hazardous gas emissions, relatively small life time, potential lead pollution and thermal management system required |
| | | Ni-Cd / Ni-MH | Toxic materials, intolerant to temperature extremes, memory effect, costly recycling, safety process and low cell voltage |
| | | Na-S | Very high operating temperature, safety concerns, light weighted and high initial cost |
| | | Medium Duration (fast response) | <ul style="list-style-type: none"> • Black start • Valley filling • Demand side management • Distributed storage • Loss reduction • Investment deferral • Contingency service • Area control • Spinning reserve • Capacity credit • T&D support |
| Pb-A | Same as mentioned for “long duration” | | |
| Na-MeCl ₂ (ZEBRA) | Safety concerns, very high operating temperature, light weighted and high initial cost | | |
| Li-ion | High capital cost, sophisticated charge control electronics required, light weighted, fire protection scheme required, safety and recycling of toxic lithium oxide & salt required | | |
| VRFB / HFB | Same as mentioned for “long duration” | | |
| FC | Same as mentioned for “long duration” | | |
| Ni-Cd / Ni-MH | Same as mentioned for “long duration” | | |
| TES | Same as mentioned for “long duration” | | |
| FES | Low energy density, constructional limitations, long recharging time due to frictional losses, large standby losses, short term power and high capital cost | | |
| Metal-air (Zn-air) | Relatively new and untested, limited shelf and cycle life, voltage drop at the beginning of discharge, electric charging is difficult and only few options available | | |
| SMES | Low energy density, adverse health impact due to extensive magnetic field, manufacturing complexity and high capital cost | | |
| Short Duration (highly frequent) | <ul style="list-style-type: none"> • Power quality • Intermittency mitigation • Transient stability • End-user application • Frequency regulation • Renewable integration • Fluctuations smoothing • Emergence power bridging | FES | Same as mentioned for “long duration” |
| | | SCES | High operational cost, infancy technology, short term power, relatively low energy density, toxic compound and high capital cost |
| | | Pb-A | Same as mentioned for “long duration” |
| | | Na-MeCl ₂ (ZEBRA) | Same as mentioned for “medium duration” |
| | | Li-ion | Same as mentioned for “medium duration” |
| | | Ni-Cd / Ni-MH | Same as mentioned for “long duration” |
| | | SMES | Same as mentioned for “medium duration” |

modeling approach for power system devices helps to organize data, configure objects and map them on to protocols, so that they are consistent and interoperable. IEC 61850 is becoming more popular and being adopted world over as global standard for power system automation. There is a consensus among research and industry stakeholders that IEC 61850 will be the communication standard of the future smart grid [213]. The research focuses on extending it to model new technologies such as EVs [214], smart meters [215], fault current limiters [216], and energy management systems [217].

The IEC 61850 information model of different components interacting with ESS is shown in Fig. 30. Information modeling is a well-established and effective method for managing information exchanges. In IEC 61850 standard, the group of data objects that serve specific functions are

defined as logical node (LNs) and composition of relevant LNs for providing information needed for a particular device is defined as logical device. While an Intelligent Electronic Devices (IED) may comprise of one or more logical devices. Hence, information models comprising of different LNs are developed for all the components of first access electricity systems.

The major components are PV system, Home Energy Management System (HEMS), battery storage system, smart meter (SM) and loads. Storage system employed in this scenario can be any of the ESS discussed in this paper. Standardized approach to control and communication has the benefit of interoperability and interchangeability, where different technologies from different manufacturers can be seamlessly integrated [218]. Accordingly, it is possible to use

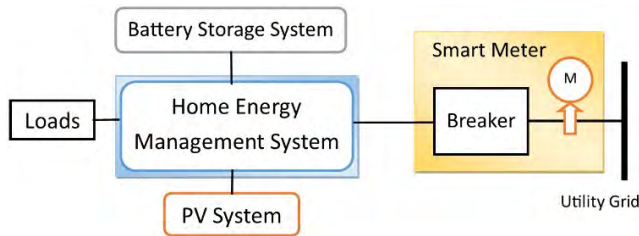


FIGURE 30. Connection of Residential-type ESS and interacting components.

EVs and stationary battery storage systems as well as more innovative systems such as graphite or paper batteries.

Standardizing communication has unwanted consequences as well. While it makes it much easier to connect new equipment and configure them, it also causes cybersecurity concerns as it opens doors to those who might have malicious intentions. Realizing this loophole, a complementary cybersecurity standard has been published, i.e. IEC 62351, for power systems that utilized IEC 61850 based systems. This is especially important for storage systems due to the scale of their impact on the grid thank to their ability to effect voltage and frequency levels, induce bidirectional power flow, and contribute to fault currents under contingency conditions.

Research in this field focuses on achieving authentication, integrity and confidentiality. In other words, new techniques are investigated to implement alongside IEC 61850 communication to ensure that only authorized devices can access the network, the stream data is genuine and is not tampered with; and sensitive data is only viewable by authorized people. Recent studies consider implementing such cybersecurity methods to systems with EVs [219], where additional authentication mechanisms are employed. Both power system operators as well as ESS owners have concerns regarding unauthorized access and undesirable operation of ESS. Such solutions help alleviate these and facilitate deployment and use of ESS in large-scale. It is certain that for more innovative optimization mechanisms to work with more ESS, an interoperable yet safe power system communication system is required [220].

V. CONCLUSIONS

Fundamental changes in power systems operation and structure necessitate use of more energy storage devices. These can be utilized for a variety of purposes such as voltage and frequency support, load shifting as well as long-term supply-demand balancing. Especially, higher penetration of renewable energy-based generation needs more storage to mitigate intermittency and low-inertia they introduce to the system. There is a myriad of choices when it comes to electrical energy storage systems. In order to select appropriate ones for a given scenario, it is imperative to know the underlying technologies, their performances and possible roles in the power system operation.

This paper reviews state-of-the-art ESS technologies along with promising future trends. Based on their capacities and

operation characteristics, potential application fields for these technologies in power system operation are also documented. Furthermore, current and future research trends that relate to ESS are also covered. The research fields are not only limited to the storage systems themselves, e.g. chemicals used in a battery's structure, and other research fields that include and relate to ESS are also covered, e.g. DERMS and Standard Communication fields.

It is safe to conclude that ESS are becoming more widespread and there are more innovative technologies appearing. As far as the individual devices are concerned, current research focuses on two major points: finding new chemical or topologies that can store more energy per unit volume and driving the construction costs down so that same energy can be stored for less cost. When it comes to system-level ESS research, the focus is on specific algorithm or application development where ESS can be used to increase the resiliency, efficiency or quality of power system operation. There are many innovative approaches such as ferrying energy with electric vehicles to where the energy is needed or using smart inverters with storage to provide voltage and frequency support in distribution networks. It is certain that more innovative solutions will appear in the future, and these will enable the transition to a fully-digitalized power networks that are energized by mostly, if not fully, by renewable energy-based generation systems.

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