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Energy Storage Systems Technologies, Evolution and Applications

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Abstract

Energy in its varied forms and applications has become the main driver of today's modern society. However, recent changes in power demand and climatic changes (de-carbonization policy) has awakened the need to rethink through the current energy generating and distribution system. This led to the exploration of other energy sources of which renewable energy (like thermal, solar and wind energy) is fast becoming an integral part of most energy system. However, this innovative and promising energy source is highly unreliable in maintaining a constant peak power that matches demand. Energy storage systems have thus been highlighted as a solution in managing such imbalances and maintaining the stability of supply. Energy storage technologies absorb and store energy, and release it on demand. This includes gravitational potential energy (pumped hydroelectric), chemical energy (batteries), kinetic energy (flywheels or compressed air), and energy in the form of electrical (capacitors) and magnetic fields. This paper provides a detailed and comprehensive overview of some of the state-of-the-art energy storage technologies, its evolution, classification, and comparison along with various area of applications. Also highlighted in this paper is a plethora of power electronic Interface technologies that plays a significant role in enabling optimum performance and utilization of energy storage systems in different areas of application.

Keywords

Energy Storage Systems, Renewable Energy Sources, Power Electronic Interface (PEI), Applications of Energy Storages

1. Introduction

In a complex and technology driven world of today's 21st century, the role of energy in its sustenance cannot be over emphasized. The ease with which it can be converted from one form to another and harnessed for man's benefit has made energy the bedrock of modern society. Central to this harnessing concept of energy utilization is the generation of electricity and the national grid which today is generally a massive network of power generating and distribution systems that now serves as the main pool of electrical energy in any nation. From its inception, power generating stations to the national grid had in times past being mostly powered using fossil fuel which has continued to emit dangerous CO_2 and other greenhouse gases to the atmosphere. The inability of distributed fossil generating systems to match their power output to peak power demand causes imbalance in both supply and demand ends across the power system. This imbalance in both supply and demand has continued to grow, and thus alter the natural inertia of the electrical network. This in turn affects the grid's frequency to become less stable and deviate from its target more rapidly than in the present day. In a bid to reduce carbon emission, there has been an increasing integration of other power generating systems such as wind, solar and fuel cells into the electrical grid. Energy Storage System (ESS) can buffer the differences between the demand and supply.

Based on energy storage technologies, ESSs can be divided into five categories which are electromagnetic, electrochemical, chemical, mechanical, and thermal [1]. Each storage system has distinctive advantages in terms of power rating, discharge time, power and energy density, response time, self-discharge losses, life and cycle time, etc., [2]. These features should be taken into account to determine their suitability for different grid support functions, such as peak shaving, and energy arbitrage.

Thus, the objective of this paper is to review ESS technologies, grid support functions and power converters for ESSs. In this paper, Section I reviews the evolution energy storage technology, where timeline of different energy storage systems was invented. Section II presents a review of the chemical energy storage technology, where different battery storage systems are detailed and assessed. Section III presents the ESS technology in which super capacitors and superconducting magnetic energy storage system (SMES) was discussed. Section IV presents a review of the thermal energy storage technology, where thermal storage systems were detailed and assessed while Section V presents a review of the mechanical energy storage system, where different mechanical storage systems are detailed and assessed. Section VI discusses applications of energy storage systems while section VII focuses on power conversion systems. Section VIII presents a detailed comparison of selected energy storage systems in terms of system specification, chemical energy storage technology, where different battery storage systems are detailed and assessed while conclusion and references sum up the paper review.

Evolution of Energy Storage Systems

ESSs have traversed a long way to reach the shape they are at today. The deployment of ESSs began roughly in the 19th century. Prior to that, ESS was not a common concept. Previously, biofuels (such as, wood) were in use since ancient times, but humans were not consciously storing energy by their usage. Batteries are the first types of energy storage that man used consciously. The term battery was coined by Benjamin Franklin in the year 1749. The first battery was invented by Alessandro Volta in 1800. He stacked discs of Cu and Zn separated by brine electrolyte [3]. Since then, there have been countless developments to the battery.

2. Electrochemical Energy Storage

Chemically, energy can be stored for a long time in the form of chemical bonds of molecules. When molecules react chemically and electron transfer takes place, energy can be produced [4].

2.1. Lead-Acid Battery

Lead-acid battery technology is based on positive and negative electrodes submerged into electrolyte which is a combination of sulfuric acid and water, lead dioxide is used as a positive electrode and lead is used as a negative electrode [5]. This type of secondary cell is widely used in vehicles and other applications requiring high values of load current. Its main benefits are low capital costs, maturity of technology, and efficient recycling. Nominal voltage of this technology cell is around 2 volts. Merits of a lead-acid battery technology include low-cost of manufacture, high specific power low cost per watt-hour, capable of high discharge currents and good performance at low and high temperatures. Disadvantages include low specific energy; poor weight-to-energy ratio, slow charging (Fully saturated charge takes 14 - 16 hours) and the need for storage in charged condition to prevent sulfating. Lead-acid battery also suffers from Limited cycle life of which repeated deep-cycling reduces battery life [6]. Lead-Acid battery cross section is shown in **Figure 1**.

2.2. Nickel-Cadmium

Cross section of the Nickel-cadmium battery is shown in **Figure 2**.

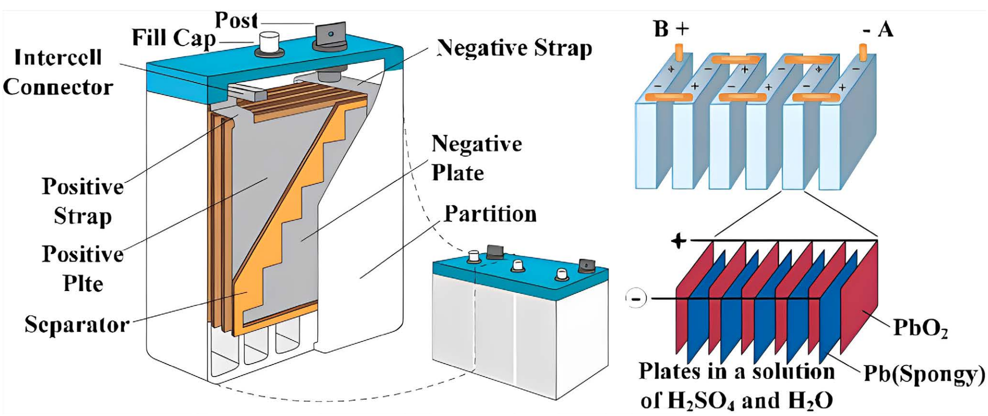

Figure 1. Lead-Acid battery cross section.

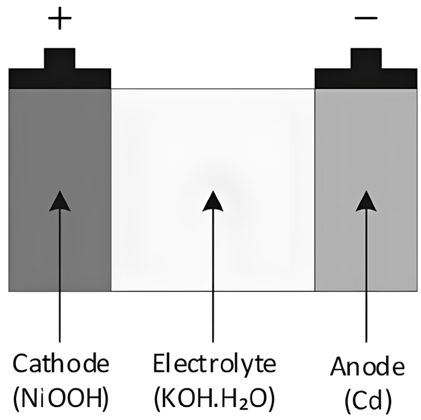

Figure 2. Nickel-cadmium battery cross section.

Nickel-cadmium (Ni-Cd) technology is type of battery technology that has in use for quite a long time. It finds application in systems that require operation in difficult environmental conditions and long battery life. Nickel cadmium technology is based on cathode made from nickel oxide hydroxide and anode made from metallic cadmium while electrolyte used for Ni-Cd batteries is potassium hydroxide [7]. Core advantages of Ni-Cd technology are ability to resist electrical and physical stress, low maintenance cost, a high number of lifetime cycles and suitability for long term storage and. Demerits of this battery technology includes high cost in comparison to the lead-acid technology, limited energy density, toxic and caustic elements in batteries and the memory effect.

2.3. Lithium-Ion

Lithium-ion (Li-ion) battery technology is one of the most advanced battery technologies widely used today. As a result of its light weight and good energy density, cellphones, smartphones, tablets, laptops, all gadgets are powered with the Li-ion battery. The Li-ion battery consists of a positive electrode-anode, a negative electrode-cathode, separator, electrolyte, and two current collectors [8]. The anode consists of lithiated metal oxide, whereas, the cathode consists of graphitic carbon with a layering structure. The electrolyte is made up of lithium salt, which is dissolved in organic carbonates [9]. Lithium-ion battery working principle is given in **Figure 3**.

Advantages of lithium-ion batteries include high specific energy and high load capabilities with power cells long cycle and extended shelf-life; maintenance-free high capacity, low internal resistance, good columbic efficiency simple charge algorithm and reasonably short charge times while disadvantages are need for protection circuit to prevent thermal runaway if stressed, degradation at high temperature and when stored at high voltage, Impossibility of rapid charge at freezing temperatures [10].

2.4. Nickel-Metal Hydride

Nickel-metal hydride technology is based on the negative electrode made from hydrogen-absorbing alloys which have the possibility to absorb releasing hydrogen and the positive electrode made from nickel oxy-hydroxide. There is a separator which separates positive and negative electrodes to prevent shorting between electrodes. Electrolyte used in this technology is potassium hydroxide (KOH) [11]. There is a current collector made of metal which minimizes the internal battery resistance. To release gases produced during the overcharging or shorting there is a self-sealing safety vent. Nickel-metal hydride battery cross section is shown in Figure 4.

Some advantages of NiMH technology are long battery lifetime, high number of lifetime cycles, good performance at the high temperatures, high energy density, good ability of recycling and the high tolerance to battery overcharging and over discharging. Disadvantages are high cost in comparison to the lead-acid

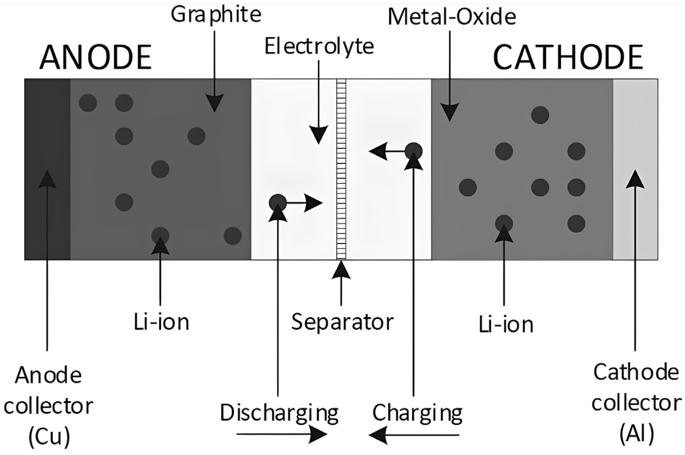

Figure 3. Lithium-ion battery cross section.

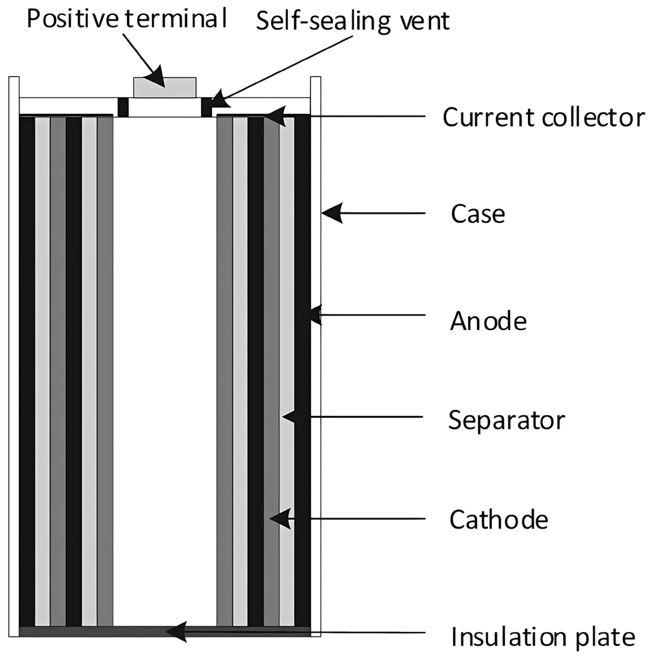

Figure 4. Nickel-metal hydride battery cross section.

technology and bad performance at the low working temperatures [12].

2.5. Sodium-Sulfur

Sodium-sulfur (NaS) battery is one of the most suitable battery technology that has being put to use in energy storage systems because of the high energy density and good maximum depth of discharge characteristic which is theoretically 100%. This battery technology is based on the use of sodium as anode and sulfur as cathode, with the electrolyte being of beta alumina ceramics. A defined advantage of this technology that the electrolyte also serves as a separator between the positive and negative terminal. As such, sodium sulphur battery technology has a low internal cell resistance because of the use a ceramic electrolyte which invariably increases its power to weight ratio and while also reducing the quantity of heat liberated internally during the charging process [13].

Detailed characteristics of sodium-sulfur battery technology are shown in **Figure 5**. Advantages of sodium-sulfur technology as highlighted in **Table 1** include high number of lifetime cycles, high energy density, capability of pulse power and good resistivity to self-discharging. Disadvantages are high cost and high temperature required for battery operation [14].

2.6. Vanadium-Redox Flow Battery

Yet another promising type of battery technology is the Vanadium-redox flow battery (VRFB). This battery technology has very good characteristics. That includes very fast response time, long lifetime, and long storage time which makes it suitable for long-term energy storage. VRFB battery technology possesses a unique characteristic in that its Power and energy are independent of the other. As such, power of this battery type depends on the number and size of the cells while its energy depends on the available electrolyte, respectively tank size [15]. Cross section diagram of Vanadium-redox flow battery is shown in **Figure 6**.

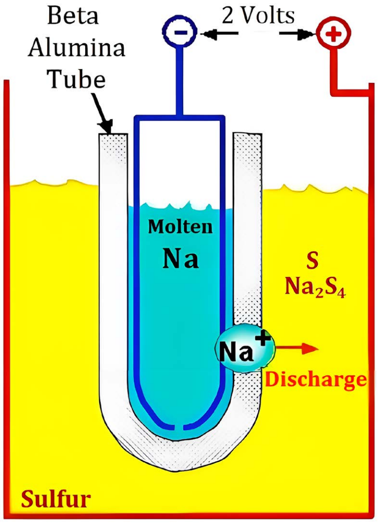

Figure 5. Sodium-sulfur battery cross section.

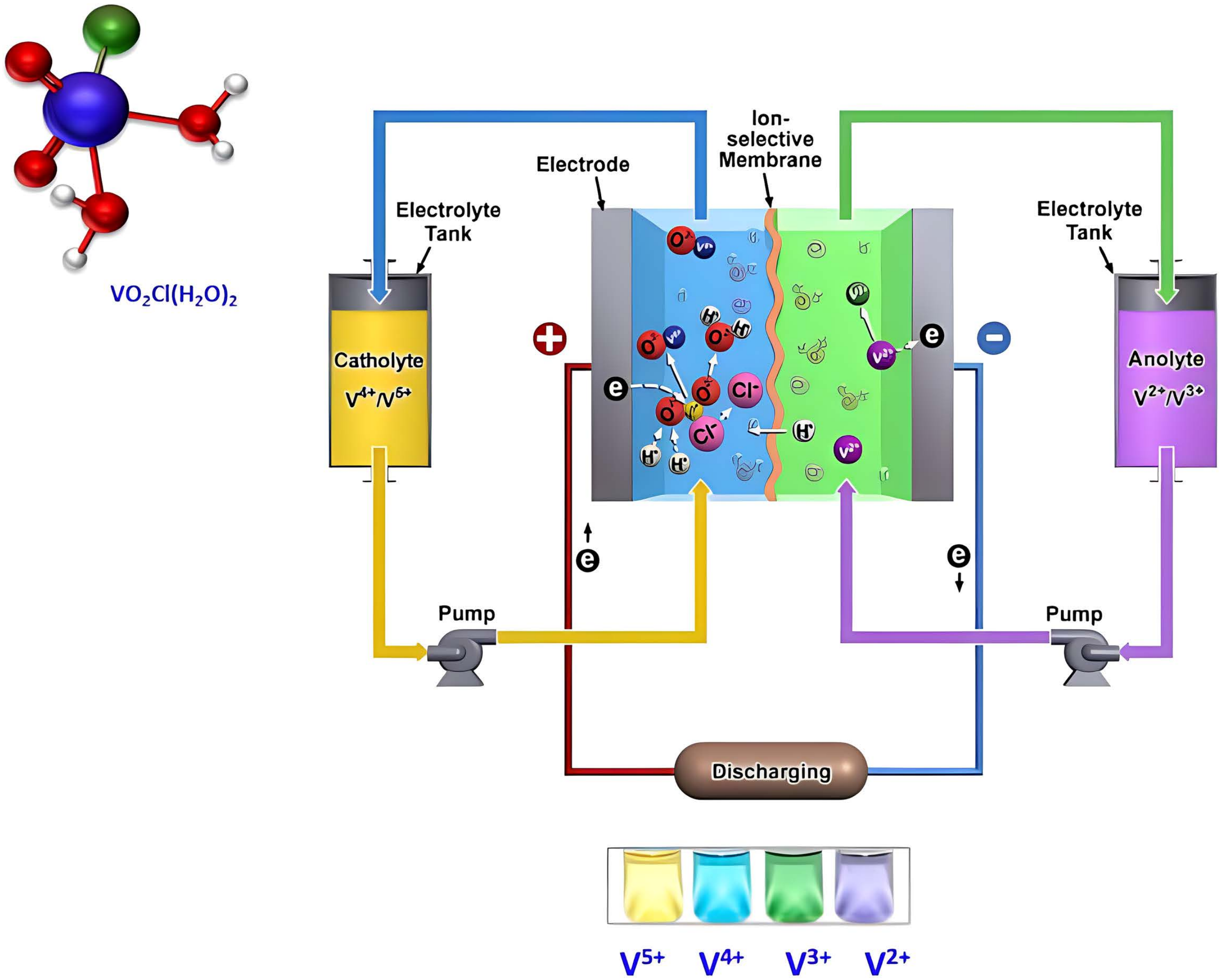

Figure 6. Detailed diagram of Vanadium-redox flow battery.

2.7. Comparison of Battery Storage Systems (BSS)

From **Table 1**, it becomes obvious why lithium ion battery technology is still the batter technology of choice when it comes to implementing energy storage system among other battery technology. This is not only due to its matured technology but primarily because of its higher specific power, energy density and efficiency when compared to other battery technology [17]. Although there are other batteries with promising specific power and energy density, these are still in the research and development stage.

3. Electrical Energy Storage Energy

3.1. Super-Capacitors

Super-capacitors (SCs) also known as ultra-capacitors or electric double layer capacitors [18] consists of at least two electrical conductors, often in form of a metal foil, which are separated by an insulating layer made of plastic, ceramics or glass as shown in **Figure 7**. When a capacitor is charged, the energy is stored

Table 1. Comparison of battery technologies [16].

characteristics	Pb-Acid	Li-ion	Ni-Cd	Ni-Mh	Nsa	VRFB
Specific energy [Wh/Kg]	25 - 50	80 - 250	30 - 80	40 - 110	150 - 240	10 - 130
Specific Power [W/Kg]	150 - 400	200 - 2000	80 - 300	200 - 300	90 - 230	50 - 150
Energy Density [KWh/m^3]	25 - 90	95 - 500	15 - 150	40 - 300	150 - 350	10 - 33
Power Density [KW/m^3]	10 - 400	50 - 800	40 - 140	10 - 600	1.2 - 50	2.5 - 33
Energy cost [€/kWh]	40 - 170	500 - 2100	680 - 1300	170 - 640	250 - 420	130 - 850
Power cost [€/kW]	250 - 500	1000 - 3400	420 - 1300	200 - 470	850 - 2500	500 - 1300
Lifetime [years]	2 - 15	5 - 15	10 - 20	2 - 15	10 - 15	5 - 15
Lifetime cycles [cycles]	250 - 2000	100 - 10000	1000 - 5000	300 - 1800	2500 - 40,000	10,000 - 16,000
Cell voltage[V]	2.21	3.7	1.3	1.35	2.71	1.4
Efficiency [%]	63 - 90	75 - 97	60 - 90	50 - 80	75 - 90	75 - 90

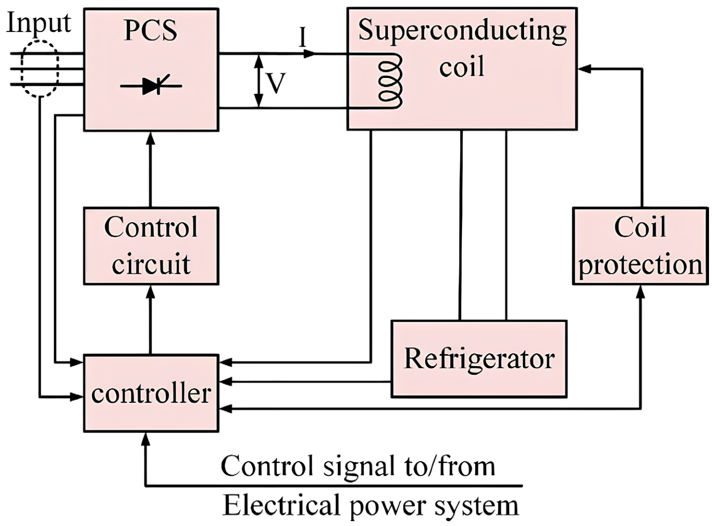

Figure 7. The super-capacitor storage system [9].

in the dielectric material in form of electrostatic field. SCs stores energy in the two series capacitors of the electric double layer which is formed between each of the electrodes and the electrolyte ions. They are capable of storing large energy density and can respond to any change in power demand in tens to hundreds of milliseconds [19].

3.2. Superconducting Magnetic Energy Storage

A superconducting magnetic energy storage system is a system that stores energy within the magnetic field of a coil contained of superconducting wire with very little energy loss. Schematic diagram of a super magnetic energy storage (SMES) system is shown in Figure 8. It occurs by inducing DC current into coil

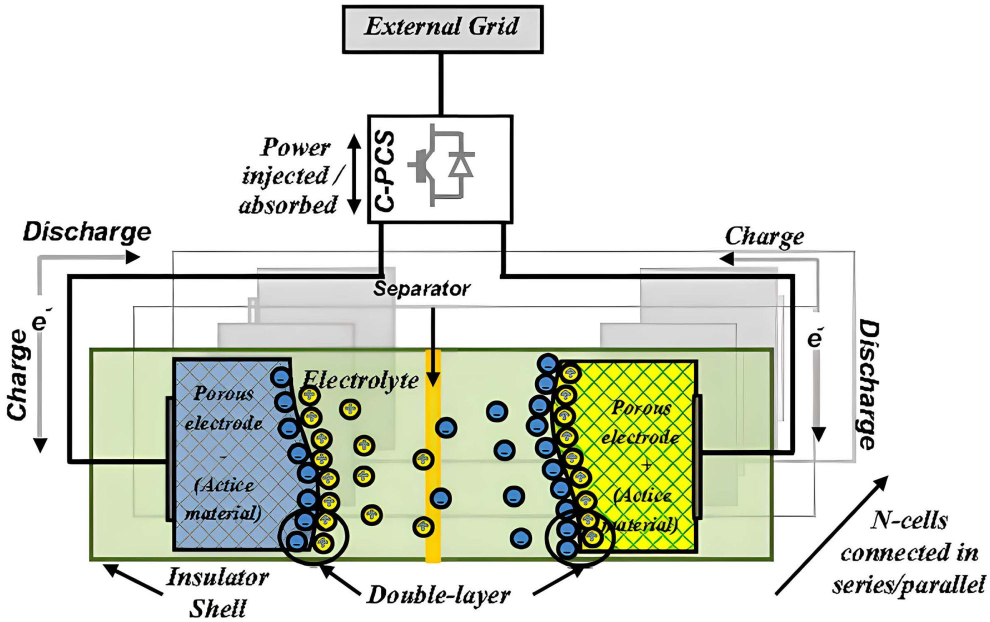

Figure 8. Schematic diagram of a super magnetic energy storage (SMES) system.

made of superconducting cables of nearly zero resistance (usually made of niobiumtitane (NbTi)) filaments that operate at very low temperature of about −270˚C [20]. SMES consists of three parts namely superconducting coil/magnet, power conditioning system and cryogenically cooled refrigeration [21]. The DC current increases during charging while the reverse is the case during the discharging operation. Although the system requires considerable quantity of energy to attain cryogenic condition and the current has to flow through non-superconducting material and solid state switches which cause resistive losses, the overall efficiency in commercial applications in the range of MW is very high [21].

4. Thermal Energy Storage Systems

Thermal storage systems are systems built to absorb heat from a wide range of sources and preserve it in an insulated storage for later use in industrial and residential applications [22]. Basically, energy is hoarded for storage and later released on demand.

Thermal energy storage systems utilize diverse methods where the input and output energy is either heat or electricity. Conventional thermal storage uses concentrating solar-thermal power (CSP) to heat the storage media, which typically is a molten nitrate salt with composition 60 wt.% $NaNO_3$-40 wt% KNO_3, also known as solar salt.

Thermal storage systems are used to act as an intermediary between thermal energy demand and supply. A storage medium can be a liquid or a solid. Thermal energy can only be stored by varying the temperature of the storage medium cool or heat other objects, or even for generating electricity [23]. Schematic diagram of a thermal heat storage system is shown in **Figure 9**.

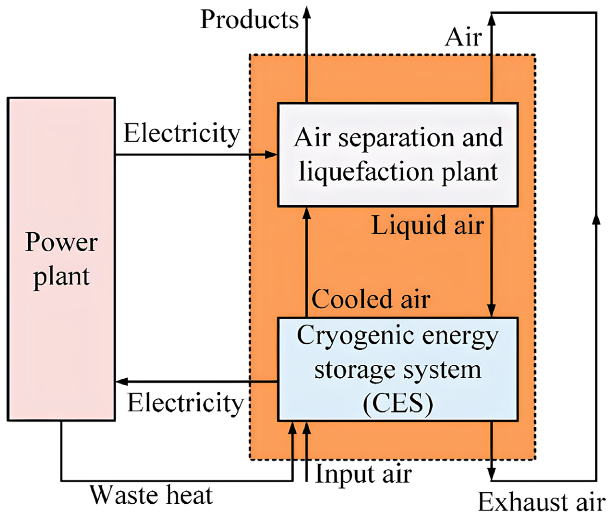

Figure 9. Schematic diagram of a Thermal heat storage system.

5. Mechanical Energy Storage

Mechanical energy is one of the oldest forms of energy that humankind has been using for diverse uses. An advantage of mechanical energy is that it can be stored easily and for long periods of time. It is very flexible in the sense that it can be easily converted into and from other energy forms [24]. Mechanical energy can appear as potential energy or kinetic energy. Pressurized gas and forced spring are two variations of potential energy, whereas kinetic energy can be stored within motion of a body. Five forms of mechanical storage systems are elaborated here. Among them, the pumped hydro storage, Liquid Air Energy Storage, Gravity Energy Storage and compressed air energy storage systems store potential energy, whereas flywheel energy storage system stores kinetic energy.

5.1. Pumped Hydro Storage (PHS)

First deployed in 1944 in Switzerland, pumped hydro storage (PHS) is one of the most popular storage techniques due to its simplicity and large storage capacity. PHS is a mature and robust technology with high efficiency of 76% - 85%, low capital cost per unit energy, long storage period, practically unlimited life cycle, and a very long life of 50 years or more [25].

The energy produced from a given quantity of water depends on the head, which is the distance between the turbines and the upper reservoir. The larger the head, the greater the energy generated for a given volume of water will be [26]. Schematic diagram of a pumped hydro storage system is shown in **Figure 10**.

5.2. Gravity Energy Storage (GES)

Gravity Energy Storage technology is a variation of the PHS technology that uses a very large piston that is suspended in a deep water filled shaft with sliding seals which helps to prevent leakage around the piston. The system operates as a

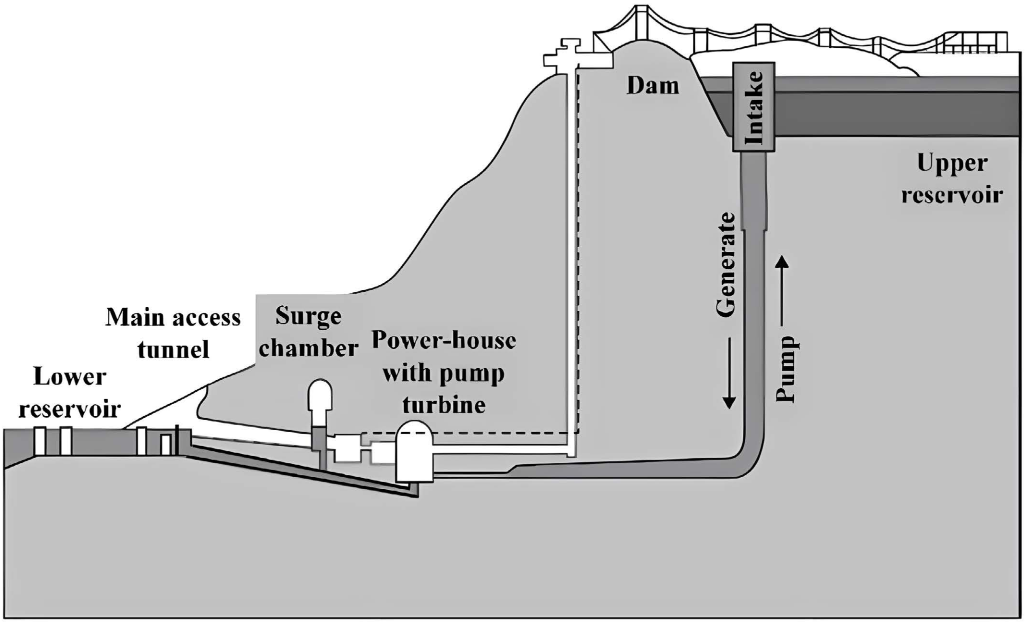

Figure 10. Schematic diagram of a pumped hydro storage system. The potential energy stored by water is converted into electricity at convenient time.

closed loop which means that the shaft is only filled with water once, mainly at the start of the operation. During the charging mode, the off peak electricity is used to drive the motor/generator which spins the pump to force water down the return pipe and into the shaft thus lifting the piston. The piston is held at the high position until when power is needed during the discharging mode. In the discharging mode, the piston drops forcing water down the storage shaft up the return pipe and through the turbine which spins a motor/generator to produce electricity [27]. Image illustration Gravity Power Module is shown in **Figure 11**.

5.3. Compressed Air Energy Storage (CAES)

The compressed air energy storage (CAES) is a technology where compressed and pressured air is utilized to store energy. The CAES plant consists of two major components—a storage vessel, and a compressor/expander [28]. The storage vessel is used to store air at high pressure without any pressure loss. The air is compressed using the compressor and, when needed, expanded by the expander. Surplus electricity during the off-peak time, *i.e.*, when demand and energy rate is low, is used to compress the air at high pressure and store it in the storage chamber. During the peak time, this stored energy is retrieved by expanding the compressed air through the expander [29]. Process Diagram of CAES is shown in **Figure 12**.

5.4. Liquid Air Energy Storage (LAES)

In recent times, liquid air energy storage (LAES), which is similar to the CAES technology, has gained much attention. In this type of storage, a liquid instead of air is compressed; this is more advantageous than the CAES system in terms of

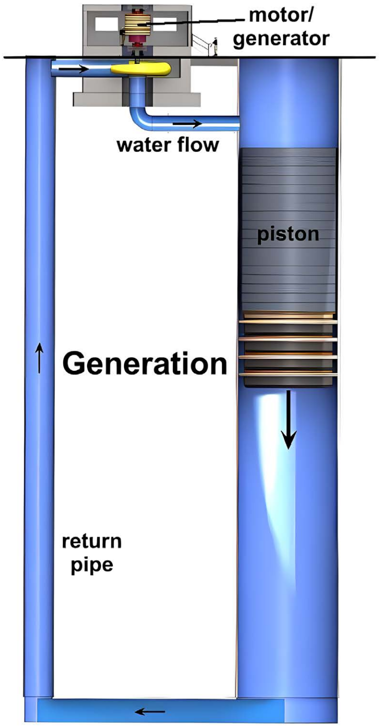

Figure 11. Gravity Power Module (GPM).

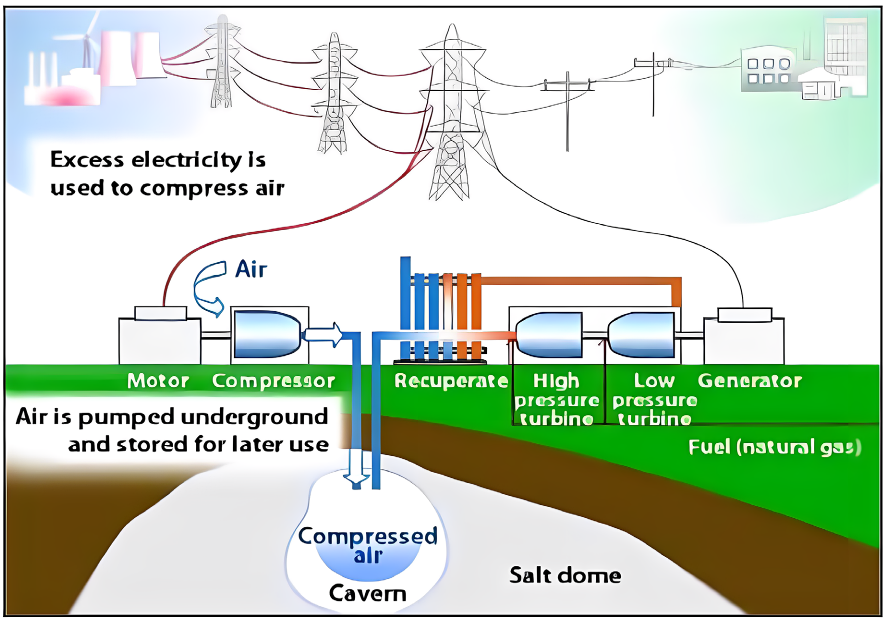

Figure 12. Process diagram of CAES.

space demands. Using liquid instead of air increases the energy storage density of the system [30]. Schematic diagram of liquid air energy storage system is shown in Figure 13.

5.5. Flywheel Energy Storage (FES)

The flywheel energy storage (FES) comprised of steel was first developed by John

A. Howell in 1983 for military applications [31]. FES possesses high energy and power density, high energy efficiency, the flywheel uses the kinetic energy, *i.e.*, rotational energy of a massive rotating cylinder to store the energy in the form of mechanical energy [31]. Through magnetically levitated bearings, this large cylinder is supported over a stator and electric motor/generator is coupled with the flywheel as shown in Figure 14.

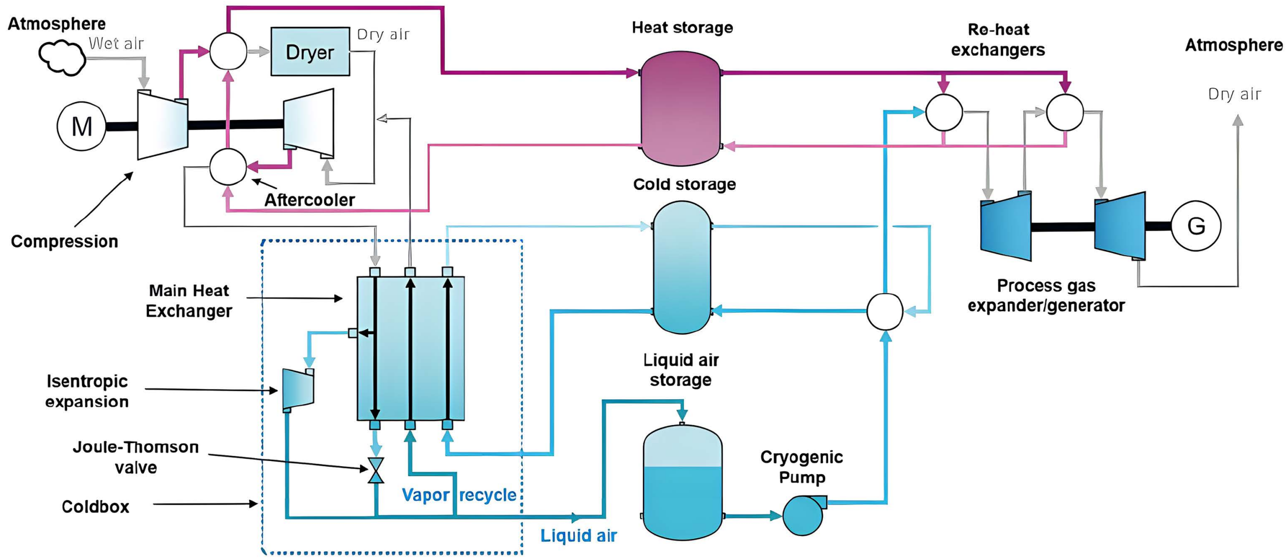

Figure 13. Schematic diagram of liquid air energy storage (LAES) system.

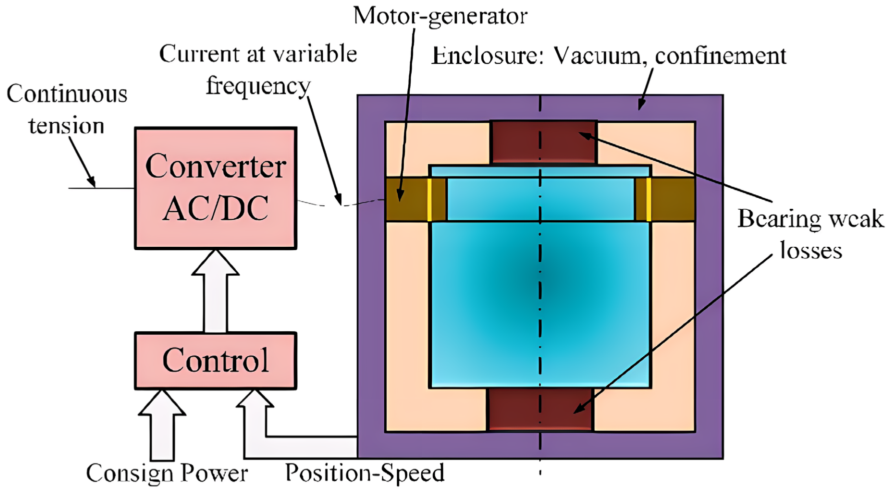

Figure 14. Schematic diagram of flywheel energy storage (FES).

6. Comparison of Energy Storage Technologies

Comparison of Energy Storage technologies is shown in Table 2 and Table 3.

6.1. Energy/Power Density

The power density of an energy storage technology is defined as the rated power output divided by the volume of the device. Its unit is W/kg or W/litre. This is

Table 2. Technical characteristics of ESSs [32] [33].

ESTs	Power Range (MW)	Energy Density (Wh/l)	Power Density (W/l)	Round Trip Efficiency (%)
FES	10 - 5000	0.5 - 1.5	0.5 - 1.5	0 - 85
PHES	0 - 0.25	20 - 80	1000 - 2000	90 - 95
CAES	5 - 1000	3 - 6	0.5 - 2	70 - 89
Pb-A	0 - 40	60 - 150	150 - 300	70 - 90
Ni-Cd	0 - 40	680 - 1300	170 - 640	85 - 90
Na-S	0.5 - 34	150 - 250	150 - 230	85 - 90
Li-ion	0 - 100	200 - 500	500 - 2000	90 - 97
VRFB	0.3 - 3	20 - 70	0.5 - 2	75 - 83
SCES	0 - 0.3	2.5 - 15	500 - 5000	90 - 95
SMES	0.1 - 10	0.2 - 2.5	1000 - 4000	95 - 97

Table 3. Technical characteristics of ESTs [32] [33].

ESTs	Life Time (years)	Response Time	Capital Cost ($/kW)
FES	10 - 15	Seconds	50 - 350
PHS	40 - 60	Minutes	2000 - 4300
CAES	20 - 60	Minutes	400 - 1000
Pb-A	5 - 15	Milli-seconds	200 - 600
Ni-Cd	15 - 20	Milli-seconds	500 - 1500
Na-S	10 - 20	Milli-seconds	350 - 3000
Li-ion	14.16	Milli-seconds	900 - 4000
VRFB	10 - 20	Milli-seconds	600 - 1500
SCES	10 - 30	Milli-seconds	500 - 5000
SMES	20 - 30	Minutes	200 - 489

slightly different from the energy density which is defined as the actual energy stored divided by the volume of the storage device (Wh/kg or Wh/litre). [34]. As shown in Table 2, HES and Zn-Air battery have very high energy density but suffer from low round trip efficiency. Other conventional batteries, CAES and LAES follow with medium energy density while PHES, SMES, flywheel and super capacitors have lower energy density. Amongst the batteries, Li-on, NaS and $NaNiCl_2$ have higher energy density than the others. Comparison of energy and power density for all selected energy storage systems is shown in Figure 15.

6.2. Life Time

Comparison of life time for all selected energy storage systems is shown in Table 3. Every energy storage technology has a definite life span that also plays a

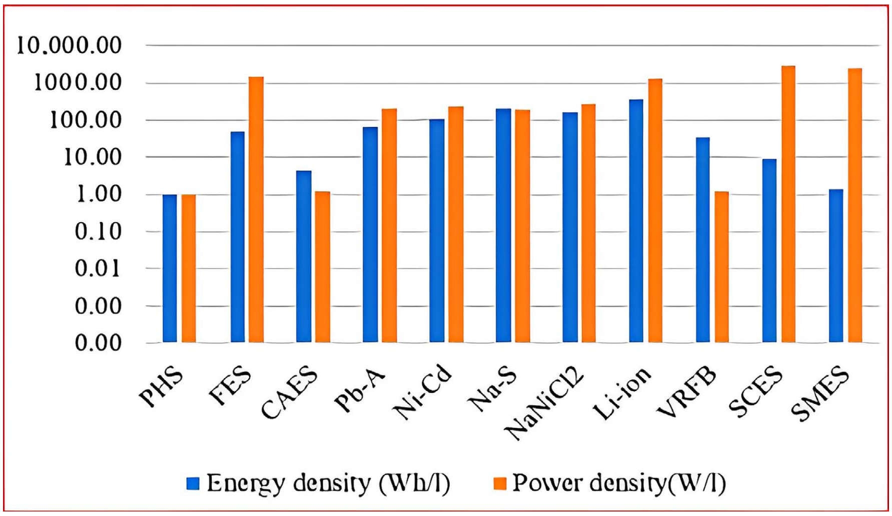

Figure 15. Comparison of energy and power density for all selected ESTs [33].

significant part in deciding whether the technology will be adopted for any given application or not. All things been equal, energy storage technologies with long life span are usually preferred from an investment point of view over those with short life span. it can be affirmed that mechanical energy storage technologies which are based on conventional mechanical engineering such as PHES, CAES, flywheel, gravity energy storage and hydrogen energy storage systems usually have long life time as their life time is mainly determined by the life time of the mechanical components [34] Battery based systems usually have short life time owing to chemical deterioration with the operating time.

6.3. Capital and Operating Costs

The cost of an energy storage technology is one of the most important factors for commercial deployment of a given energy storage technology. For detailed analysis, the cost of any given energy storage technology should include both the capital and operating costs. The operating cost covers the cost of operation, maintenance, disposal and replacement. The auxiliary components used by some energy storage technologies add to the total capital cost of the system. As a result of this, some energy storage systems tends to be only economically feasible above a minimum energy content and power output [34].

Table 3 shows that CAES has a lower capital cost per kWh than the PHES but also suffers from low round trip efficiency. Flywheel, SMES, super-capacitors have very high power density and capital cost per kWh but low capital cost per kWh per cycle which makes them suitable for applications that require high power output for short duration.

6.4. Round Trip Efficiency

Comparison of round-trip efficiency for all selected ESTs is shown in **Figure 16**. The round trip efficiency is the ratio of the electricity output from the storage device to the electricity input to the device during one charge/discharge cycle. It

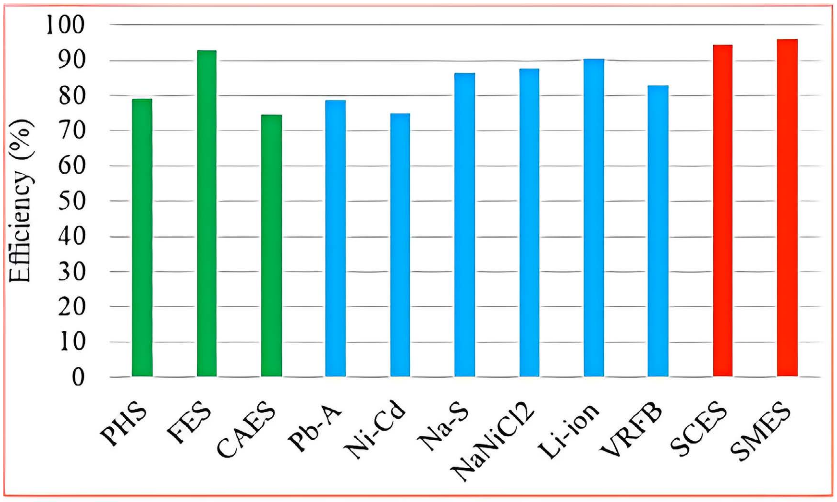

Figure 16. Comparison of round-trip efficiency for all selected ESTs [33].

accounts for the losses which occur as a result of storing and withdrawing energy from the energy storage device [34]. As shown in **Table 2**, SMES, flywheel, super-capacitors and Li-ion battery have very high efficiency (>90%). These are followed by PHES, CAES, batteries (50% - 90%) and then HES, Zn-air battery technologies which have low round trip efficiency (<50%).

6.5. Response Time

This denote how fast the energy storage system can release the store energy or respond to quick demand of stored power. Depending on the energy system requirement, some applications may require a very fast release of the stored energy to meet the system energy demand [34]. From **Table 3**, super capacitors, SMES and flywheel have very fast response time in the order of milliseconds. This is followed by batteries with response time in order of seconds, then PHES and CAES in minutes.

7. Applications of Energy Storage Systems

In the earlier days, the sole purpose of ESSs was to provide backup power to the system and serve as a secondary support for the utility. As supply and demand imbalance grew, coupled with the need to reduce greenhouse emissions with the advancement of technology and continuous ongoing research, ESS has now become a significant part of power and utility system [2]. Novel works carried out in this regard have highlighted the beneficial roles of ESS in global renewable energy mix [35]. The study reviewed and analyzed the various elements of renewable integrated deregulated power systems and the pivotal roles of energy storage systems in its actualization. The main objective of the review was the maximization of system profit, maximization of social welfare and minimization of system generation cost and loss by optimal placement of energy storage devices into renewable energy systems. ESS must be properly sized to act as buffer between the demand and supply imbalance. Additionally, ESS technology and control must be suited for the applications

7.1. Intermittent Balancing

Primarily, different energy storage technologies can be used to achieve intermittent balancing of the electricity supply [36]. With such seasonal variations occurring for days, weeks or months in which case efficiency of the storage plays a crucial role or momentarily such as seconds to minutes as the case with load following, frequency regulation and voltage support in which case the response time particular ESS storage technology becomes key requirement.

7.2. Arbitrage

This involves using electrical energy storage technologies to store electricity during periods of low demand and subsequently sell it during periods of high demand. This type of storage requires technologies which can achieve long storage duration (hours to days), together with high round trip efficiency. **Figure 16** shows that technology such as batteries, CAES, LAES, GES, and PHS can be used to achieve this type of application.

7.3. Black Start

During emergency system power collapse, ancillary electricity supply resources may be needed to be restart such failed mechanisms without pulling electricity from the grid. This would require an electrical energy storage technology which should be used to quickly restart such failed power or machine infrastructure devoid of any energy intensive auxiliary equipment. Electrical energy storage technologies such as batteries and super capacitors are best suited for this.

7.4. Mobile Application

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

7.5. Voltage Regulation and Control

Due to dynamic changes do occur, on electric power systems creating a dynamic response or changes in active and reactive power and thus influencing the magnitude and profile of the voltage in the networks, the need to mitigate this effect, energy storage systems becomes necessary. ESS can be used to control constant maintain and dynamic voltage behaviors.

7.6. Standing Reserve

Energy storage technology can be used as reserves to deal with network constraints arising when the electricity demand exceeds the supply, which can happen when load forecasts are inaccurate, or in case unexpected plant outage occurs.

8. Power Electronic Interface (PEI)

As novel as energy storage systems are, these systems would hardly be applicable without some form interface circuits that can be used to feed energy in and out of these systems. Typical distributed ESSs are mostly batteries, supercapacitors, SMESs and flywheels which are mostly categorized as DC ESSs. This would voltage converters to convert from Alternating Current (AC) to Direct Current (DC) and vice versa for all storage devices except mechanical storage devices e.g. PHES and CAES (Compressed Air Energy Storage). To this end, a PCS would be required to acts as a rectifier while the energy storage device is charged (AC to DC) and as an inverter when the device is discharged (DC to AC) [37]. The customization of the PCS for individual storage systems has been identified as one of the primary sources of improvement for energy storage facilities, as each storage device operates differently during charging, standing and discharging. Typical power converters include bidirectional DC/DC converters (Bi-DC/DC), bidirectional DC/AC, and bidirectional AC/AC.

8.1. Bidirectional DC/DC Converters (Bi-DC/DC)

This is basically a non-isolated Bi-DC/DC structure that is based on the buck/boost converter topology, which as presented in Figure 17. The topology is very advantageous in applications where access to the DC bus neutral-point is needed. The buck-boost converter design has a low number of power electronic devices, which in turn doubles down on its lower costs of implementation and higher reliability than other converters. Its major drawback is that it cannot be

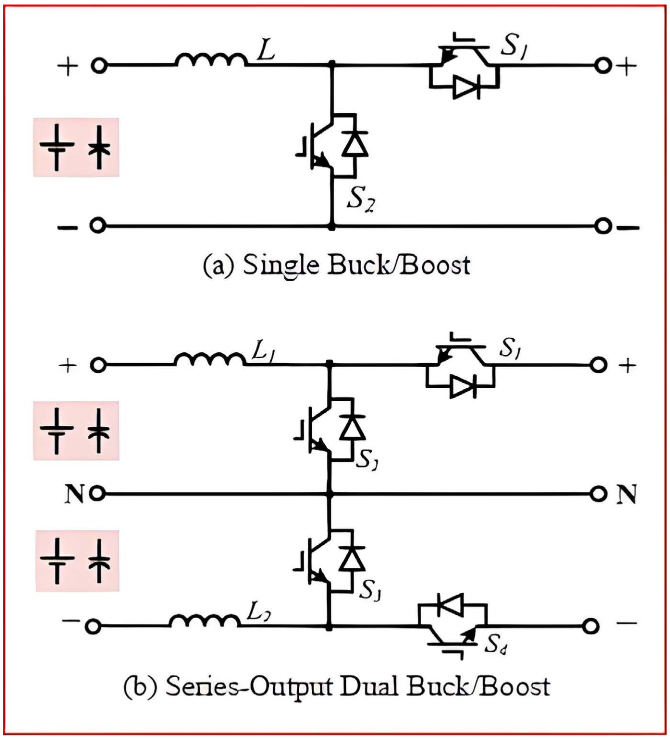

Figure 17. Bidirectional buck/boost converter.

used in applications where isolation is required. Another area weakness is that its voltage step-up ratio is relatively low, making it unsuitable for low-voltage ESSs.

8.2. Bidirectional DC/AC Converters (Bi-DC/AC)

This power switching topology is one of the most widely used DC-AC converters basically consists of two-level inverters as shown in Figure 18, which can be single-phase and three-phase. This type of bidirectional two-level DC-AC inverter has a compact design and high reliability.

8.3. Bidirectional AC/AC Converters (Bi-AC/AC)

Bidirectional AC-AC converter is a matrix converter, of other types of converter topology already discussed. Presented in Figure 19. Matrix converter utilizes an intermediate DC link that may consist of the Bidirectional DC/DC Converters and Bidirectional two-level DC-AC converter which have their merits. However, more bi-directional switches are involved, which makes the system more complex and costly. Furthermore, parallel DC and AC busses are usually adopted since most ESSs are commonly combined to achieve a high power rating, large scale or high reliability for utility applications.

9. Conclusion

In this paper, energy storage technologies along with applications and power interface circuits have been reviewed. Based on the review, the following conclusion

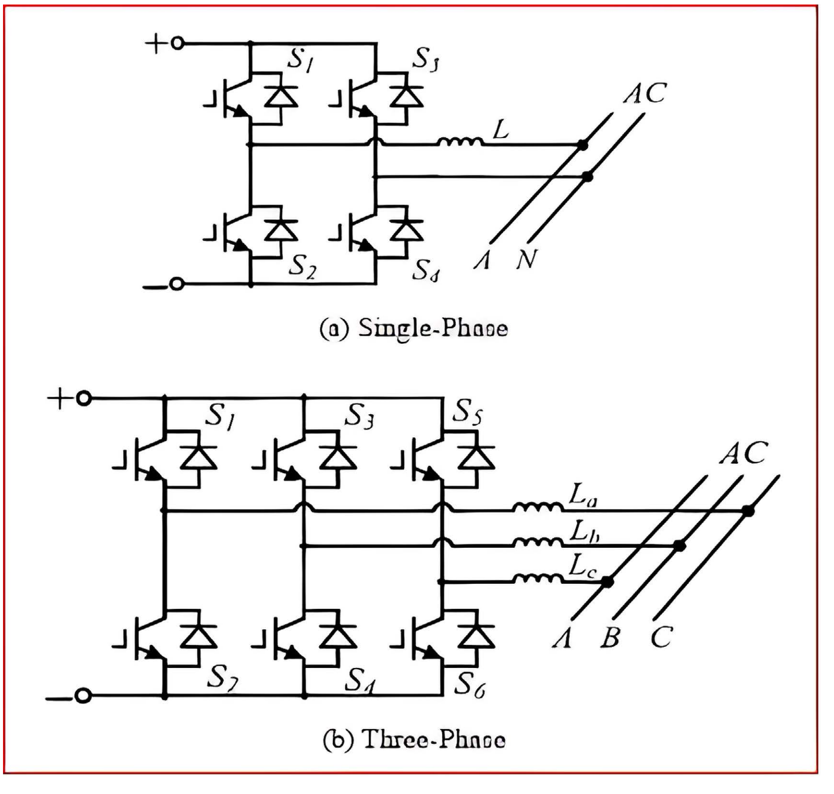

Figure 18. Bidirectional two-level DC-AC converter.

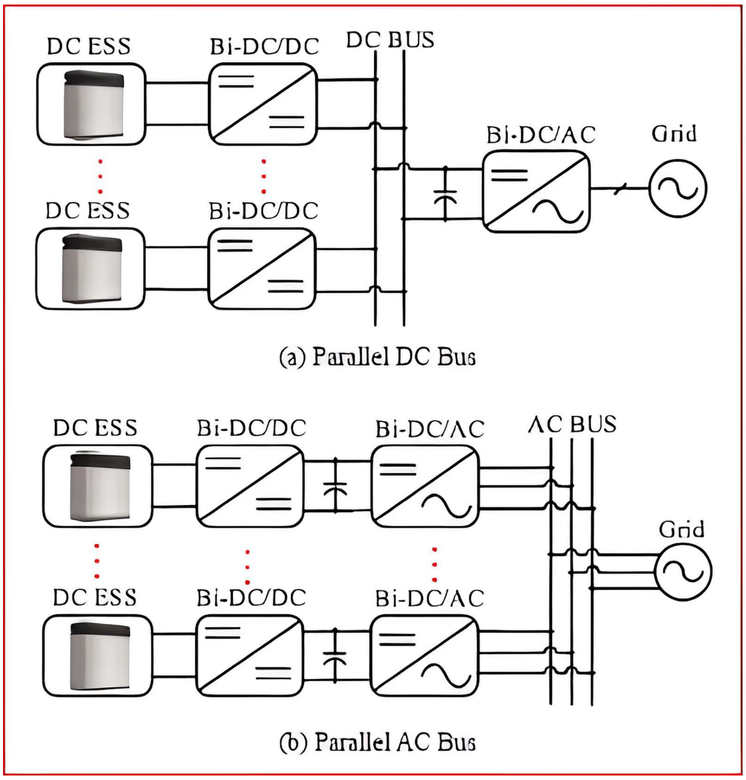

Figure 19. Matrix AC-AC converter.

has been drawn. Although there is a plethora of energy storage systems, there is not a single storage system that can meet all the requirement in terms of required application and design constraints. This implies that single energy storage systems can be suited for specific applications based on the characteristics of the ESTs. It is thus evident from the comprehensive review that electrochemical energy storage systems (batteries) are the front runner of the ESTs to be used when high power rang, high energy, power densities, longer discharge time, fast response time, and high cycle efficiency are paramount interest. To this end, most types of ESTs have widespread application, potential in the renewable energy sector as well as in the power system.

Among electrochemical energy storage system, Li-ion batteries are considered as a more competitive option for grid-scale energy storage applications such as RESs utility grid integration due to their high energy density (350 Wh/l) and power density (1250 W/l), being lighter in weight and smaller in size, high cycle efficiency (90.5%), low daily self-discharge rate (0.19), rapid response time (sec), and low environmental impacts. These unique advantages have made lithium ion battery the battery of choice for telecommunication, power systems, radio, and television systems, solar, UPS, electric vehicles, automobile, forklifts, emergency lights, etc.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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