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Comparative analysis of electrochemical energy storage technologies for smart grid

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ABSTRACT

This paper presents a comparative analysis of different forms of electrochemical energy storage technologies for use in the smart grid. This paper addresses various energy storage techniques that are used in the renewable energy sources connected to the smart grid. Energy storage technologies will most likely improve the penetrations of renewable energy on the electricity network. Consequently, energy storage systems could be the key to finally replacing the need for fossil fuel with renewable energy. It is hard to evaluate the different types of energy storage techniques between themselves due to the fact that each technology could be used in a different way and are more like compliments. Subsequently, for the purposes of this paper, it is seen that the use of energy storage technologies will increase the supply, and balances out the demand for energy.

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1. INTRODUCTION

The population of the world is growing rapidly and we need to utilize all our resources properly without wasting them. Energy storage devices make sure that energy is used efficiently and the remaining energy is used is stored for a later use. The power grids that we have today are local grids that grew and were interconnected over time. Central generation power stations started delivering power to huge areas by high capacity power lines. These lines then branch off and supply power to smaller users. Since electricity was supplied, electric companies have to send out workers to collect data used to provide electricity. Recently, this has been replaced by computers. Energy storage is the way energy is being conserved in a particular form and then released when needed in the same form or converted to a different form [1]. The term smart grid (SG) basically means computerizing an electric grid. The SG is very reliable because it uses technologies that improves the fault detection and allow self-healing of the network [2]. This makes the supply of electricity more reliable. SGs are more flexible as they can handle different energy sources and some of the issues that come with them. SG has anticipated the improvement of efficiency of energy infrastructure mostly in the demand-side management, and it leads to lower power prices. SG makes the relationship between suppliers and customers more flexible [2]. The major point is that storage techniques are the basis of the future of SG. Without adequate storage techniques, there will be no way to reliably meet the energy demands of the future. The current electrochemical energy storage techniques that will be explored in this paper include Lithium-ion based batteries, sodium-based batteries, flow batteries, nickel-based batteries, lead acid batteries and metal air batteries.

Renewable energy is energy that can be converted from natural resources. These resources can be renewed because they are abundant in nature. Some examples of renewable energy resources (RERs) are wind, solar, hydroelectricity, biomass (waste), and geothermal, etc. These resources can be converted into electricity to reduce energy shortage. Renewable energy has its advantages and disadvantages. Major advantage of renewable energy is that it can never be depleted. The different facilities require very little maintenance reducing the cost of production. It is also environmentally friendlier because they do not emit pollutants or create waste that destroys the air and our ecosystem. On the other hand, the drawback is the amount of energy produced is not as huge as that of fossil fuel. It depends greatly on nature to produce power and is not always reliable. It is also expensive to create and install because it is a new technology, but with time the price will reduce as more people switch to renewable energy. A great way to sustain this renewable energy is through the energy storage devices [3].

Electricity that is produced is fixed over short periods of time. The amount of power demanded varies at different times of the day and power grids controllers have to respond to these changes. The gap between power that is demanded and power being supplied varies in sizes. This gap depends on the speed at which the peak-matching generating equipment is ramped up and the speed at which the demand is expected to rise. Peak shaving is used to help this problem [4]. To have more flexibility while managing power grids, operators use peak shaving that uses power equipment with fast responses to match small increases in demand. Fast-responding power systems make the gap between power demanded and power supplied smaller. Storage devices save the energy that is not used and stores it for later use. They make this electricity available whenever it is needed. Electric energy storage gathers excess electricity produced at off-peak hours and releases the stored energy at peak hours. These storage system provides grid frequency regulation, voltage support, and operating reserves. This enhances the grid stability and reliability [5].

With the increasing importance of energy storage in power system operations, significant efforts have been spent on improving the technical performance of energy storage technologies. The issue of energy storage arises with the need to match the demand and supply of energy to individuals. With the advent of electricity brought about more concern for the need of energy storage due to its prior nature of being used up when generated or converted to another form or energy. However, new trends on energy shows ways these generated energy could be stored and harnessed. In the area of renewable energy, it’s necessary for energy to be stored and combined to help the demand on green energy [6]. More work has is being done to increase the assimilation of various energy storage methods into the smart grids which are connected to RERs. This is largely due to the intermittency that arises with these resources. Energy storage in these systems will help to provide a buffer for periods of imbalance with power demanded and supplied [7, 8]. Improved storage facilities will also help the RERs to address transmission issues that result from geographical challenges and easing availability for consumers. In these grids, generally, super capacitors are used for short-term storage, which runs is considered to be about a few microseconds, while batteries are used for longer-term storage.

2. CLASSIFICATION OF ENERGY STORAGE TECHNOLOGIES

A battery is an electrochemical device that stores electrical charges through chemical reactions. There are various types of batteries invented which are commonly used around the world today. However, two main categories are primary (disposable) and secondary (rechargeable) batteries. A primary battery/ non-rechargeable battery can convert chemical reactions into electricity only once [9]. Figure 1 depicts the schematic diagram of primary battery.

On the other hand, when looking at a secondary/rechargeable battery cell, we see that this cell has electrodes that can be reused by passing electricity back through it. This type of battery can be reused many times by recharging, it is the rechargeable cell [10]. Figure 2 depicts the schematic diagram of secondary cell. Typically, a set of 4 alkaline batteries costs around 2.74$ with a capacity of 0.0171 kWh, this corresponds to a cost of 160.23 $/kWh. Batteries are about 267,000% more expensive per kWh than household electricity. When using batteries on a smart grid we see that the energy storage applications use rechargeable batteries for load leveling. They do this so that they may store electric energy for use during peak load periods. Also, this happens for energy sources such as storing solar energy during day time periods [11]. Broadly, the energy storage technologies have been classified into mechanical, electrical, electrochemical and thermal energy storage technologies. Figure 3 depicts the classification of various energy storage technologies, and their technical features are presented in Table 1 [12-14].

Batteries are made up of several series connected cells connected by an electrolyte for easy electron transfer and electrodes (cathode and anode). As we go deeper in the types of batteries, we shall see that the names batteries are directly related to its composition [15]. The charging and discharging of a battery is a

Redox (reduction-oxidation) process. During discharge, electrons are transferred from the battery to the load through the process of oxidation. When charging, electrons are transferred to the battery when a voltage is applied to its terminals. This is referred to as a reduction process [16].

New technologically advanced batteries are being fabricated, designed, and built as the trend of using motor vehicles is increasing. It has a serious environment impact which is leading to the air pollution in large cities and densely populated areas. Batteries are can be found in many different forms which include lithium-ion, sodium-sulfur, flow, lead acid, etc. Because of their high cost and/or short lifetime, they are used in a limited number of applications. For storage techniques to be implemented there needs to be monetary incentives made available that will allow these storage techniques to become a reality. Most residential customers do not have the money to put out to purchase these storage techniques. And commercial customers do not want to totally front these costs either. There need to be a specific cost sharing plan and pricing policy established between the government, commercial customers, residential customers, and utility regulators.

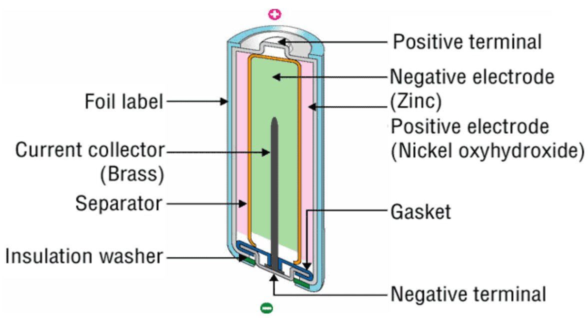

Figure 1. Schematic diagram of primary battery

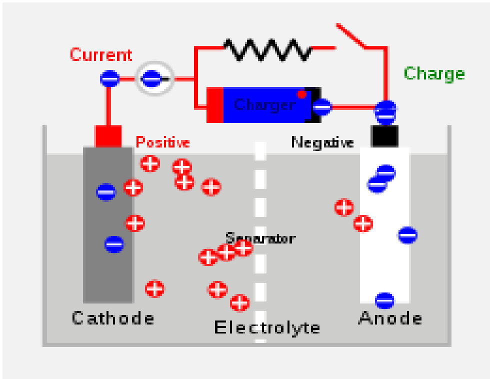

Figure 2. Schematic diagram of secondary cell

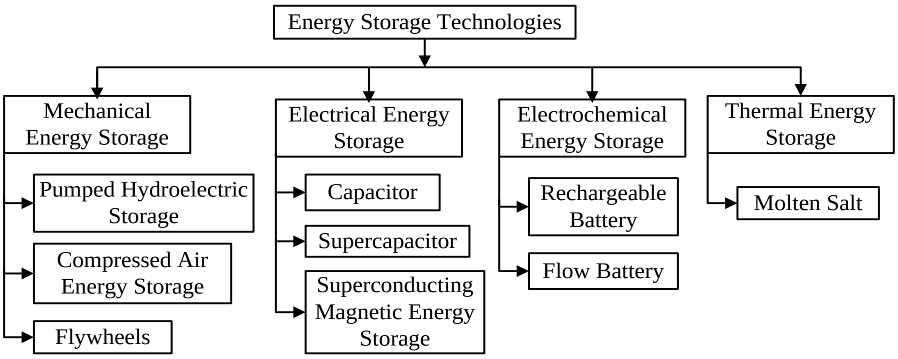

Figure 3. Classification of energy storage technologies

Table 1. Technical features of various energy storage technologies

	Pumped Hydroelectric Storage	Compressed Air Energy Storage (CAES)	Flywheels	Rechargeable Battery	Flow Battery	Molten salt
Power rating (MW)	(100-1,000)	(10-1,000)	(0.001-1)	(0.1-40)	(0.1-100)	(1-150)
Energy density (Wh/l)	_	(2-6)	(20-80)	(150-400)	(20-70)	(70-210)
Power density (W/l)	(0.1-0.2)	(0.2-0.6)	5,000	(120-10,000)	(0.5-2)	_
Storage duration (hours)	(4-12)	(2-30)	(seconds-hour)	(1min-8hour)	(1-10)	hours
Efficiency (%)	(70-85)	(40-75)	(70-95)	(70-98)	(60-85)	(80-90)
Self-discharge	0	0	(1.3-100) %	0.05-20%	0.2%	heat loss
Response time	(seconds-minutes)	(seconds-minutes)	<seconds	<seconds	<seconds	minutes

3. COMPARATIVE ANALYSIS OF ELECTROCHEMICAL ENERGY STORAGE

Several types of rechargeable batteries that are considered in this paper are lithium-ion based batteries, sodium-based batteries, flow batteries, nickel-based batteries, lead acid battery and metal air batteries. Further research needs to be done on storage techniques to continue to increase the benefits while reducing the associated costs. There needs to be effective cooperation between government agencies, utility companies and regulators, and consumers that allows for both political and cost hurdles to be overcome. Nevertheless, storage techniques show great potential to help the RERs and the smart grid to meet the world's growing energy demand. The comparative analysis of electrochemical energy storage is presented next:

3.1. Lithium-ion (Li-ion) based batteries

Li-ion batteries are quite inexpensive, have high energy and power densities and highly efficient. Similar to other batteries, it is composed of an electrode (negative and positive contacts) and an electrolyte. The composition of these batteries include: negative electrode has carbon, positive electrode has metal oxide, and electrolyte has lithium salt. Figure 4 depicts the schematic diagram of Li-ion battery. These batteries have high energy and power densities, high efficiency, low self-discharge, good charge-discharge characteristics, no memory effect as compared to nickel-based batteries. The capacity parameters are: specific power is (250-340) W/kg, specific energy is (100-250) Wh/Kg, energy density is (250-620) Wh/l, charge/discharge efficiency is (80-90) %, self-discharge rate is (8-31) %/month and nominal cell voltage is (3.6-3.7) V. Applications of utility applications, automobile and consumer electronics. Cost of this battery is 0.47$/Wh. Li-ion batteries do not pose a huge environmental impact. However, these batteries tend to explode when exposed to high temperatures or short circuited. The major disadvantages of Li-ion batteries are expensive, requires power electronics, sensitive to high temperatures. If overcharged, positive electrode decomposes, separator gets damaged and electrolyte liberates gases. There haven't been any recent break through with this technology apart from research to improve the power density, costs, recharge cycles, and safety.

There are various types of lithium-based batteries are available in the market such as lithium iron phosphate, lithium nickel oxide, lithium manganese oxide, lithium nickel cobalt aluminum oxide, etc. The anode material of these batteries consists of graphite and cathode consists of oxide variants of lithium metal amalgams. Nowadays, lithium-ion batteries are used in electric vehicles (EVs) as they have light weight and relatively high energy density. Li-ion batteries are also used in smart phones, laptops, UPS, aerospace and military applications [17].

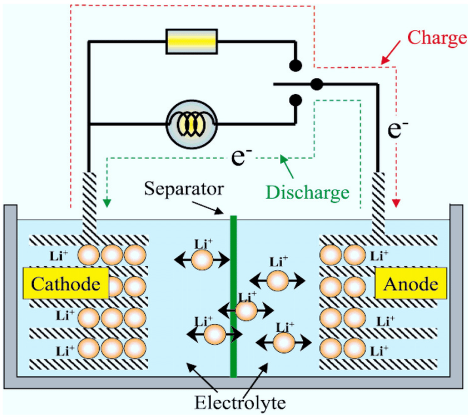

Figure 4. Schematic view of Li-Ion battery

3.1.1. Lithium-sulfur (Li-S) battery

The electrochemical reactions of Li-S battery are different from that of Li-ion batteries. Li-S batteries are very light weight due to light atomic weights of lithium and moderate weight of sulfur. Currently, best developed Li-S batteries have specific energies of about 500Wh/kg with an average voltage of 2.15 V with a theoretical specific density of 2800 Wh/l. Due to its light-weighted nature, Li-S batteries can be most efficiently used in electric vehicle (EV) batteries. Also, due to their high specific capacity, they can also be used for grid-based storage [18].

3.1.2. Lithium iron phosphate (LFP) battery

Lithium iron phosphate batteries are rechargeable batteries where the reactions are reversible. These batteries are safest of all other Li-ion batteries. These batteries show excellent life cycle of 2000 cycles. As compared to other batteries, they get charged quickly with less time. Due to no thermal runaway, these batteries are safe, no damage is caused during excessive discharge even at zero, and they produce no waste and are environmentally friendlier.

3.1.3. Lithium-air battery

Lithium-air battery has highest possible specific energy. Li-air batteries have the potential to achieve 3620 Wh/kg (when discharged to Li_2O_2 at 3.1V) or 5200 Wh/kg (when discharged to Li_2O at 3.1 V), due to the high energy density of lithium metal (3458 Wh/kg). If the oxygen supplied is not included in the calculation, Li-air cells offer an energy density of 11,000 Wh/kg, which is approximately equal to Gasoline (13,000Wh/kg). Therefore, Li-air is competitive with liquid fuels. Efficiency of lithium air batteries is currently limited by incomplete discharge at the cathode. These batteries are used in personal electronics, electric vehicles and large scale grid storage [19].

3.2. Sodium based batteries

Sodium (Na) has high negative potential and has high specific capacity. Na salts are abundant in nature, they are cheap and even nontoxic. These batteries stably operate at room temperature. Sodium-sulfur batteries and sodium nickel chloride batteries are fall into this category.

3.2.1. Sodium-sulfur (Na-S) battery

They have high efficiency of charge and discharge rate and no self-discharge. The operating temperature of this battery is usually kept at 300ºC to maintain the electrolyte in the liquid form. Sodium-sulfur (Na-S) batteries have energy density of (150-240) W/kg, power density of (150-230) W/kg and they have long cycle life up to (5000-6000) cycles [20]. These batteries are used in electric vehicles, stationary applications, aerospace and forklifts.

3.2.2. Sodium nickel chloride battery

Sodium nickel batteries are also known as zero emission batteries research activity (ZEBRA) batteries. ZEBRA batteries have high specific energy. Compared to Nickel metal cadmium (NiMH), these batteries have better energy density. The internal resistance of ZEBRA battery is very low at high levels of charge, they are expensive, have higher self-discharge rate and these batteries can withstand overcharge. ZEBRA batteries operate at very high temperature of about 350ºC which is a major issue and even when batteries are not in use they need to be kept connected continuously to the main supplies to keep the battery hot. When batteries gets cooled completely, it takes about 24 hours for reheating [21]. ZEBRA batteries are used in EVs or hybrid EVs and they are suitable for traction applications.

3.3. Flow batteries

Flow battery consists of two separate liquids flowing on either side of a membrane, where the chemical components dissolved in liquids provides the chemical energy contained within the system and separated by a membrane [22]. The features of these batteries include: flexibility in system design, competence in scaling cost, decoupled energy density, they are structurally similar to a fuel cell, power and energy can be independently sized, high efficiency, long durability and reliability, fast responsiveness and reduced environmental impact. These features allow them to be a promising storage type in stationary storage of energy from intermittent sources such as wind and solar [23]. Typical flow batteries include vanadium redox flow battery, zinc-bromine battery, etc. The key features of these batteries are presented next:

3.3.1. Vanadium redox flow battery

Among various redox flow battery metal ion combinations (zinc-cerium, zinc-bromine, vanadium-cerium, magnesium-vanadium, vanadium-polyhalide), the most successful technology is the vanadium redox battery and it is the only technology that has reached effective commercial fruition. It uses vanadium/vanadium dissolved in aqueous sulfuric acid. An advantage is that by using the same metal ions in both electrolytes, the electrodes and membrane are not cross-contaminated and the cell capacity does not decrease with time, allowing for a longer lifespan [24].

3.3.2. Zink-bromine (Zn-Br) battery

Zn-Br is also called as semi-flow battery, because during charge, much of the energy will be stored by zinc-metal plating on the anode plates in the electrochemical stack. This battery consists of zinc as the anode and bromide as the cathode, which are separated by a microporous separator. On the anode side, the electrolyte is water-based, while on the cathode side, the electrolyte is an organic amine compound [25].

3.4. Nickel-based batteries

Nickel-based batteries are categorized into Nickel metal hydride and nickel-cadmium batteries. The brief description of these batteries has been presented next:

3.4.1. Nickel metal hydride (NiMH) battery

The NiMH batteries have high energy density, low cost, high self-discharge rate, low internal impedance, reduced memory effect, less tolerant of overcharging, longer life cycle, and they are environmentally friendlier. The NiMH battery is a secondary/rechargeable battery, where the reactions are reversible. The negative electrode used in NiMH battery is metal hydride, the positive electrode used is nickel oxyhydroxide and the electrolyte used in potassium hydroxide. The anode is made up of metal hydride where the metal hydride is an alloy of either zinc, vanadium, chromium, titanium etc. The cathode is made up of nickel oxyhydroxide. Both the anode and cathode are separated by an insulator which is made up of polypropylene. The entire NiMH battery is kept in a glass or steel container. The electrolyte used in this battery is potassium hydroxide. These batteries are used in cameras, electronic devices such as computers, EVs, medical instruments and equipments, industrial standby application and in high power static applications such as uninterrupted power supply (UPS), smart grid and telecommunications.

3.4.2. Nickel-cadmium (Ni-Cd) battery

Ni-Cd battery is basically a category of Nickel batteries such as NiMH, Ni-Zn, Ni-Fe, Ni-Cd and Ni-H_2. These batteries have low internal resistance, high energy density, requires low maintenance, high reliability, but relatively low cycle life [26]. They have wide temperature ranging from (-40^o to 70^o)C, which depends on the construction and has high self-discharge up to 20% of loss per month. These batteries have high energy density (50-70) Wh/kg and also has relatively low cycle life (2000-2500) cycles. The Ni-Cd batteries have been used in emergency lighting, portable devices such as laptops and mobiles, UPS, telecommunications and generator starting, etc.

3.5. Lead acis battery

Lead acid batteries are the most affordable batteries for energy storage. They have low price, good reliability, high voltage per cell, long cycle life, relatively lower specific energy (30-50 Wh/kg) due to the weight of lead, lifetime of 5 to 7 years. The lead-acid battery is now the most widely used rechargeable electrochemical storage source in the world. They represent about 60% of all the installed power from all the rechargeable batteries. Lead acid batteries are used in UPS, hybrid electric vehicles, traction and automotive applications, lighting, grid-scale energy storage, etc [23].

3.6. Metal air batteries

Zinc-air battery falls into the category of metal air batteries. This battery is a primary/ non-rechargeable battery, where the reaction is irreversible. These batteries have highest energy density as compared to all other disposable batteries, environmentally safe and have unlimited shelf life, i.e., these batteries can remain usable for longer time. Zinc air battery is used as a main power source in hearing aid, military radio receivers, voice transmitters, and continuous-drain applications, etc [27]. Various characteristics of different electrochemical batteries have been presented in Table 2.

Table 2. Characteristics of different electrochemical batteries

Battery Type	Efficiency (%)	Cost (€/kWh)	Life Span (cycles)	Operating Temperature (ºC)	Energy Density (Wh/kg)	Self Discharge (%/month)
Lead acid	72-78	50-150	1000-2000	-5 to 40	25	2-5
Lithium-ion	100	700-1000	3000	-30 to 60	90-190	1
Nikel Cadmium (NiCd)	72-78	200-600	3000	-40 to 50	45-80	5-20
Soium Sulphur (NaS)	89	400-500	2500	300 to 350	100	0
Metal Air	50	50-200	<100	-20 to 50	450-650	Negligible
Zinc Bromine (Zn-Br)	75	360-1000	3500	0 to 40	70	Negligible
Vanadium redox (VRB)	85	360-1000	10000	0 to 40	30-50	Negligible

4. CONCLUSION

The conclusions drawn from this paper are: i) banks of lead-acid batteries are commonly used to stabilize electrical systems by supplying extra power and maintaining voltage and frequency levels, ii) lead acid batteries have very low life spans when charged and discharged frequently, iii) flow batteries store electrolytes outside itself and circulate these electrolytes to generate electricity. Because these batteries create a substrate but are not involved in any chemical reaction, the flow batteries have long life spans, iv) nickel-metal hydride have relatively low energy densities and are very sensitive. They tend to have problems with overcharging, v) rural locations utilize portable sodium-sulfur battery systems to provide power for small time periods, vi) Lithium-ion batteries are commonly used in mobile phones and laptop computers. In comparison with nickel-cadmium and lead acid batteries, they have a much higher energy density. Their long lifetimes make them a very good cost option, and vii) manufacturing of batteries poses as huge safety and environmental risk due to the large number of chemicals involved.

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