Technologies for the Energy Storage Solutions: A State of Art

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Abstract

The increased awareness of ecological issues and impact of fossil fuels on it, forcing power engineers renewable energy sources for electricity generation. But there are certain inherent problems of renewable energy such as its capacity, variable generation due to atmospheric conditions and its size. To overcome these problems, Energy Storage Solutions (ESS) are important and make resilience of energy grids.

The ESS are very important and essential for reliable and uninterrupted power supply to different loads. The importance of energy storage is further increased due to fast growing renewable energy sources like wind, solar PV generation and biomass and their variability in energy production.

This paper aims at different technologies of the existing ESS and an emerging alternative Gravitational Battery (energy Vault).

The comparison of ESS (mechanical, electro-chemical, electro-magnetic, thermal-energy storage and other latest technologies) is done in terms of efficiency, cost, charging -discharge cycle, size and it’s environmental impact, etc.

Keywords

Energy storage; Battery,;Electro-magnetic energy storage; electro-chemical energy storage; mechanical energy storage; pumped storage; hydrogen storage; pumped storage; gravitational batteries.

Introduction

The electric power grid operates based on a delicate balance between source of energy supply and energy consumed by the consumer. If this balance is disturbed by change in demand, then stability of power supply gets affected and in turn affect the voltage variation and frequency variation. These conditions affect the reliability of supply. This balance can be easily maintained by the electricity storage during the imbalance conditions (energy supply $\neq$ demand) by energy storage systems. The ESS could provide financial benefits besides the power reliability and ecological advantages. The size of energy storage and their deployment could assist the grid for better and efficient operation and reduce the chances of brownouts during peak power requirements.

The cost, size, scalability, life, maintenance and the charging -discharging cycles of electricity is mainly dependent on the technology used for energy storage. Guney and Tepe [1] in their paper described in detail about energy storage solutions with their categorization, characteristics, merits and de-merits. Aneke and Wang [2], Luo et al. [3]also discussed about different technologies used in ESS along with their applications and performances.

The important energy storage solutions are -

1. Mechanical energy storage - It includes all the ESS which follow potential energy and kinetic energy storage such as hydraulic pump storage, gravitational batteries, flywheel and high pressure gas storage.

2. Electro-chemical energy storage

It includes batteries such as Lead-Acid, Nickel-Cadmium (Ni-Cd), Sodium-Sulfer (Na-S), Lithium Ion (li-ion), flow batteries and fuel cells.

3. Electro-magnetic energy storage

It comprises of super conducting magnetic energy storage systems (SCMES). The SCMES is a latest technology. It stores electrical energy in the form of magnetic field, produced by the flow of direct current in a superconducting coil at very low temperature called cryogenic temperature.

4. Thermal energy storage systems

It deals with the energy storage system which is consisting of molten salt to store energy. It has high kWh/m^3 density ranges from 400 to 870. In past, many review papers are available on salt hydrate reactions ESS, (like Donkers et al. [4], Ding et al. [5], Yan et al. [6], Tatsidjodoung et al. [7], Trausel et al. [8], Richter [9]. The liquid like water (which is easily available, cheap and high specific heat) is preferred in this method for low/medium temperature energy storage. At 70 degree C temperature gradient it can store about 290 MJ/m^3.

5. Electro-Static Energy Storage

Super or ultra capacitors are using conducting polymers as the electrodes. These devices can store approximately 10 kW/kg. The storage time is short or typically up in seconds and 1–5 MW/m^3 size. The cost is around 10–15 €/Wh. The only limitation is their high cost [10].

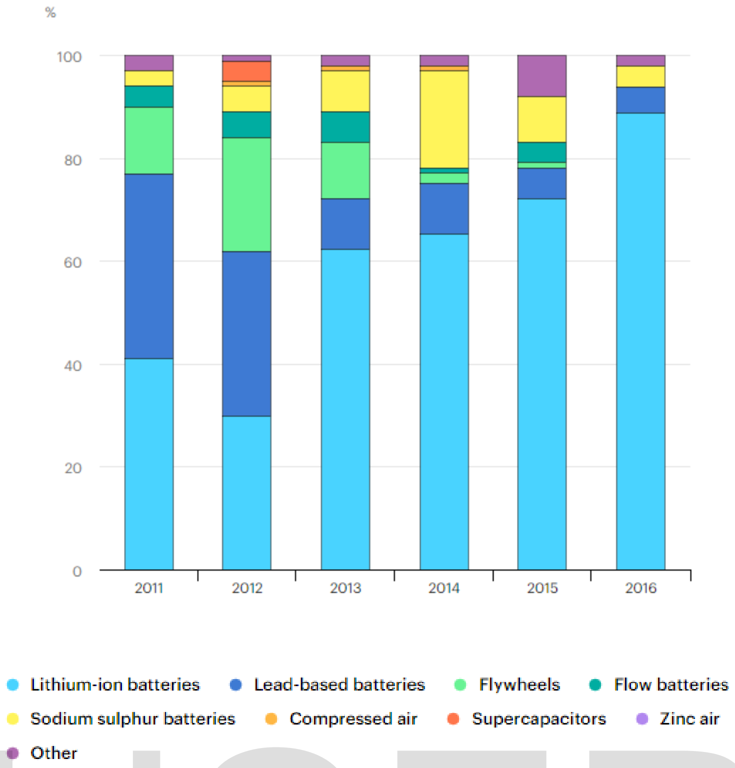

Fig. 1 Different proportions of ESS

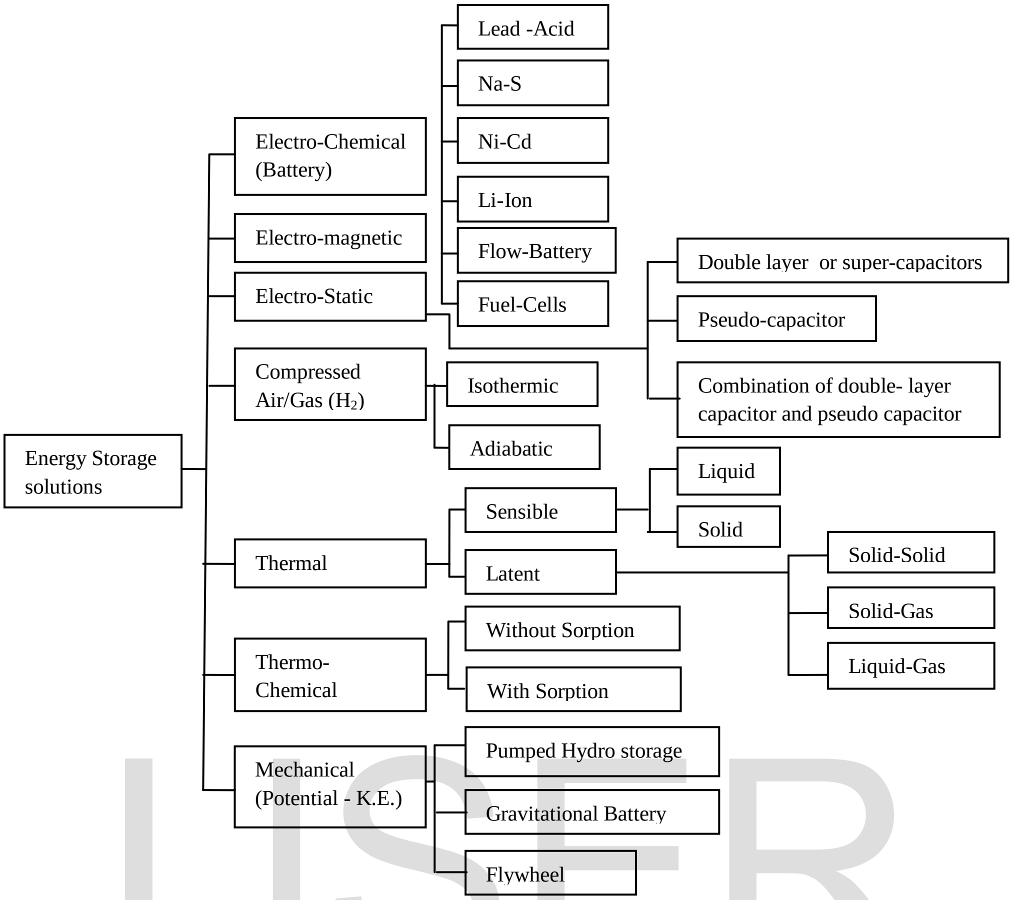

Fig. 2 Different types of ESS

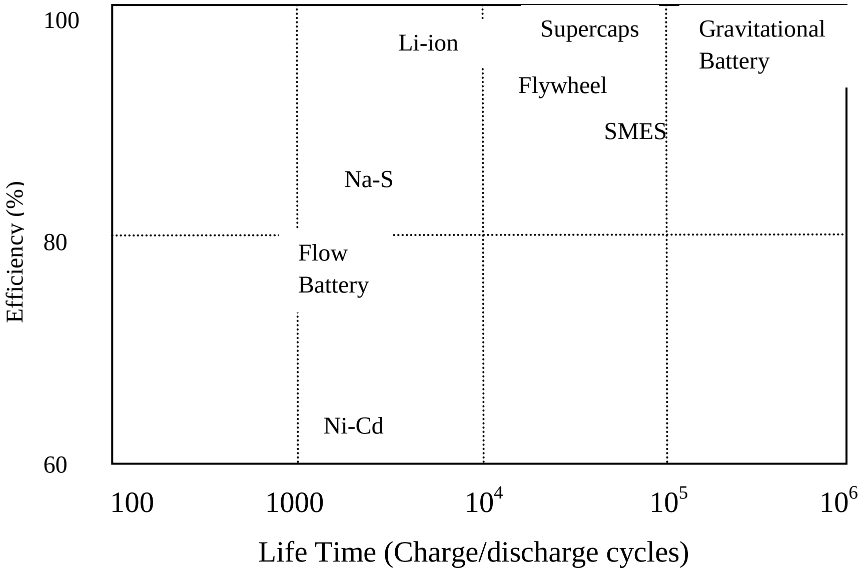

Fig. 3 Efficiency versus Life time of different ESS

The diverse proportion of ESS in actual applications is shown in Fig. 1. Fig. 2 shows different types of ESS. Also a comparison of efficiency with respect to their life time of different energy storage solutions is shown in Fig. 3. One by one all these technologies are discussed in the paper, then finally compared them at the end of the paper and concluded.

1. Mechanical ESS

a. Pumped ESS - Excess electrical energy is utilized to raise water level by pumping to elevated reservoir and increase its potential energy. This potential energy is utilized when elevated reservoir water is released and passed through a mechanical turbine which converts the water kinetic energy into mechanical energy and finally, generate electricity[11].

b. Gravitational Battery- This is a cost-effective, non-degradable with time, zero energy loss, gravity-based ESS, which is not dependent on ground terrain. The gravitational batteries have round trip cycle efficiency about 90% as compared to conventional lead acid batteries whose efficiency is quite lower. Also its cost /kWh, eco-friendly, long life ESS and scalable upto any limit without any problem. In this high density, low cost bricks or any solid block may be used with some control software to operate motors to lift these bricks with 4,6, or 8 crane arms and form a tower type structure. This ESS deliver all the advantages of a pumped hydro ESS at a very cheaper cost, require lesser land space and independent of topography (terrain). It is quick responding (respond in ms and get full power in less than 3 seconds), run vital short and medium term auxiliary services eg. rotating reserve and black start etc. This ESS accelerates the shift to a world fully powered by renewable energy sources. It has following benefits [12]:

- Easy and robust construction
- Simple to mount anywhere
- Brick materials may be waste materials and bricks constructed on-site
- High scalability
- Full depth-of-discharge (DoD) energy storage does not degrade over the lifespan.
- Very cost effective solution (only in 15% cost of Li-Ion battery, this storage can be prepared).
- No effect of weather conditions as in other batteries.

c. Flywheel- Electrical energy is utilized to speed up a mechanical flywheel (i.e. a heavy mass rotor) which preserves the kinetic energy (K.E.) which is directly proportional to mass of rotating body and square of its velocity. If there is shortage of energy, this stored K.E. is utilized to rotate a generator and meet the requirements. Some mechanical flywheels make use of magnetic bearings and run in a vacuum to eliminate air drag. This type of flywheel achieves speed up to 60,000 rpm. Flywheel ESS is having long life, good efficiency about 90%, capacity ranging from 3-133 kWh[13].

d. Compressed Gas/Air- Electrical energy is employed to compress gas/air to a very high pressure (up to 703069.6 kg/m^2 and stock in underground vessels. This pressurized gas/air is used to generate electrical energy by expanding in turbine generator.

On the other hand fuel cell are quite good in terms of their response time. The efficiency is also fairly constant throughout its load variations from zero to 100% output whereas the efficiency of expansion turbine generator falls w.r.t. its output. The only drawback of fuel cells are their cost, capacity and location.

Electro-chemical ESS

a. Batteries ESS- Batteries as ESS is a common solution for domestic applications in off-grid and UPS systems. This ESS can use Li-ion, Lead Acid, Ni-Cd, Cd-Iron or reusable alkaline batteries.

The lead Acid batteries are very commonly used in small solar power plant for domestic use because they are cheap (cost/Wh), simple in manufacturing, quick responding and less self discharge. There are some problems of these batteries like they can't be kept in discharged condition, low Wh/kg, problem of spill out of acid (limits its use in wheeled application), limited number of full discharge cycles, not eco-friendly, produce acid fumes and gases during charging. To overcome these problems lot of research has been done to modify its design and develop lead acid AGM, lead acid gel, lead carbon based battery which combines the merits of super capacitor and lead acid battery for fast charging and discharging.

The pioneer work done by G.N. Lewis in 1912 on Lithium -ion batteries and fully rechargeable battery developed in 1980s. Lithium -ion batteries are quick charging and light in weight for same capacity as compared to lead - acid batteries and hence best suited for electric vehicle. Also there is no problem of acid spill out as in lead-acid batteries. Each cell of Li-ion battery produce 3.6 V in comparison to 2V in lead-acid, Ni-Cd batteries, so less number of cells are required to produce same voltage. There are certain problems of Li-ion batteries such as it is fragile, expensive, heat up during use, which needs proper battery management system to control the heat generation, over voltage and over current. The different characteristics of battery energy storage are compared in Table -1.

Table -1 Comparison of different characteristics of ESS

Characteristics ↓	Different ESS →							
	Battery				Super Caps	Flywheel	SMES	Gravitational Battery
	Lead - Acid	Ni-Cd	Reusable Alkaline	Lithium-Ion				
$/kWh	50-100	400-2400	210-250	9k-1.3k	1.2k-1.5k	-	1k-10k	100-200
Energy Density (Wh/kg)	30-50	45-80	80-100	110-160	1-15	5-200	0.5-75	-
Efficiency	80%	85%	90%	95%	90-95%	70-80%	90-95%	90-95%
Life Span* (80%of initial capacity) Number of	200-300	1500	50	500-1000	$>10^6$	$>10^4$	$>10^4$	$>10^6$

cycles								
Charging time	8-16 hr	1hr	2-3 hrs	2-4 hr	1-10 sec	15 min.	1-10 sec	2-10 hr
Overcharge tolerance	high	moderate	moderate	Very low	Very low	high	Very low	high
Self discharge	5%	20%	0.3%	10%	50%	20-50% in 2 hrs	50%	0%
Voltage of individual cell	2.0V	1.25 V	1.5V	3.6V	2.75 V	-	10.0 kV	-
Routine Maintenance	3-6 months	30-60 days	Not required	Not required	Not required	Not required	Not required	Not required
Energy storage	Medium	Medium	Medium	Medium	Short term	Short term	Short term	Long term

* depends upon the charging and discharging cycle of batteries ESS.

Hall and Bain [14], Baker [15] had nicely given an overview of electro-chemical ESS including flow batteries,

Lead-acid, Li-ion, Na-S, Ni-Cd and Ni-metal hydride batteries and super-capacitors (Supercaps). Hou et al. [16] compared the performance for super-capacitors and Li-ion batteries. Nitta et al. [17] mentioned basic properties, opportunities and issues related to material research for lithium battery ESS. They also proposed how to minimize the size of active materials, preparation of composites and coatings on active materials, its doping and changes in electrolyte. Watanabe et al. [25] study focus on use as electrolyte materials for Li-sulfur batteries, Li/Na ion batteries and Li-oxygen batteries.

Thermal ESS

In this ESS electrical energy is employed to produce or remove heat from the fluid to increase or decrease the temperature and maintained at that temperature. For example the energy is utilized to reduce temperature of water or manufacture ice when is less demand and then used during peak electricity period [18-24].

Electric vehicle during charging

Now the number of e-vehicles are increasing with a faster rate which put up a new challenges in grid systems related to power system stability, harmonics introduced by them and transferring pollution from one place to other if the power is produced by conventional fossil fuel.

The technological and economical prospective of different energy storage solutions have been compared in Table - 2.

Table - 2Merits and de-merits of different energy storage solutions (adapted from [26])

Energy Storage		Advantages	Disadvantages	Remarks
Batteries	Lead Acid	Cheap	Low Wh/kg	Very common electrochemical energy

		Mature technically	Long charging time Limited life High maintenance Toxicity	storage device
	Ni-Cd	Mature technically	Expensive Low Wh/kg Toxicity	Famous in utility energy storage applications (sub-station backup)
	Li-ion	High Wh/kg Quick response Fast charging	Expensive Life cycle dependent on level of discharge	-
Super Caps		High Wh/kg	Interdependency of cells voltage imbalance between cells and max. voltage threshold affects its life cycle	
SCMEES (Magnetic)		Quick response Life is independent of duty cycle High efficiency High reliability No pollution	High cost Large magnetic field and proper shielding is required	Cryogenic refrigeration is required for this ESS
Flywheel		High Wh/kg Less space requirement Technically matured	Safety and Noise problems High $/kWh	Used for uninterrupted power supply and power quality application High rate of power injection
Pumped hydro		Technically matured High capacity Long life No pollution	Geographical constraint Initial Cost is high Low Wh/kg Use water and land, both are pecise	Cost is site specific High operating and maintenance cost

		Water evaporation	
Compressed air/gas	Technically matured High capacity	Efficiency is pressure dependent Leakage of Gas/Air Safety issues Installation site constraint	Cost is site specific High operating and maintenance cost
Gravitational battery	High capacity High Wh/kg Quick responding High efficiency High reliability Eco friendly Long life No storage losses	Safety issues	Used to store when excess energy available

Conclusion

The conventional power generating plant consumes large amount of fossil fuels (nuclear, coal, oil and gas). These pants adversely affect the environment and increase carbon footprints. Hence, renewable energy became popular, but unfortunately, these sources are weather dependent and could not produce sufficient energy whenever is needed. Also a lot of variability in power generation is the main concern. To overcome these problems, energy storage solutions are very important. Numerous energy storage solution successfully used in the past, but there are certain issues with them. The main issues of earlier energy storage solutions are storage loss, efficiency, not eco-friendly, storage capacity, response time, power and energy density. The increased awareness about the environmental issues related to fossil fuels and resilience of grid, energy engineers are paying their attention to different ESS. The importance of ESS further enhanced by variability of power production in renewable energy sources like solar PV -generation, wind or bio mass generation etc. In this paper, the different ESS have been discussed and are compared based on their life span, energy density, size, cost and degradation.

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