

# Energy Storage Systems – Comparative Study



## Engineering

**KEYWORDS :** PHESS, CAESS, BESS, SCESS, SMESS, Efficiency

**Chetan Upadhyay**

Research Scholar, FTE, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India

**Dr. Hina Chandwani**

Associate Professor, FTE, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India

### ABSTRACT

Although many varieties of energy storage technologies are available today, this paper gives analysis for the Energy Storage Systems (ESSs). Usage of ESS depends on application, period of storage, energy capacity and effective cost. It is divided into major three applications – Power Stability (PS), Power Bridging (PB), and Energy Management (EM). This paper presents the comparative study of different Energy Storage Systems

### INTRODUCTON

Energy Storage is a well established idea and still relatively not much popular. ESS (Energy Storage System) such as pumped hydroelectric energy storage has been used since 1929 [1] to level the daily load on the network between night and day. ESS has become realistic option for: Integrating renewable sources, power quality, increasing distributed power generation, redesigning the electricity market.

ESS optimizes the existing generation and transmission infrastructures, prevents expensive upgrades, and reduces power fluctuations from renewable resources by preventing their large scale penetration into network. There are many causes which hurdle in the commercialization of ESS – devices: Lack of experience, Inconclusive benefits, High capital costs, Cost Distribution. Devices are generally rated as: Application, Storage Capacity, Period of Storage, Cost and Expansion in Future. Here, in this paper, a brief comparison of various Aces is given.

### CLASSIFICATION

The various methods of Energy Storage System have been classified in: 1) Pumped hydroelectric energy storage System (PHESS), Underground Pumped Hydroelectric Energy Storage System (UPHESS), Compressed Air Energy Storage System (CAESS), Battery Energy Storage System (BESS), Flywheel Energy Storage System (FESS), Super capacitors Energy Storage System (SCESS), Super Magnetic Energy Storage System (SMESS). Further the detail description of each ESS is given here:

### PHESS: PUMPED HYDRO ELECTRIC ENERGY STORAGE SYSTEM

It is widely used around the world. The above ground and underground storage is possible. In 2006-07, there was a net capacity of 38.306 GW of pumped storage installed in EU-27, or 5 % of total net installed generation capacity [2]. PHESS units have used mostly fresh water but in 1999 PHESS using seawater as the storage medium was constructed which was made of anti-corrosive material. A typical PHESS facility has from 120 ft of low capacity to 900 ft of high capacity hydraulic head.

It is the most mature and largest storage system available. It requires large reservoirs located at different levels and number of pump - turbine units.

During off – peak electrical demand, water is pumped from the lower level reservoir to the higher level reservoir where it is stored until it is required. Once needed the water in the upper reservoir is released through turbine-generator set that produces electricity. The efficiency of latest PHESS is of 70 – 85%. Figure 1 describes about PHESS. The power capacity is given by:

$$\text{Power Capacity} = \rho gQH\eta \quad (1)$$

Where:

$\rho$  = mass density of water, kg/m<sup>3</sup>

$g$  = acceleration due to gravity, m/sec<sup>2</sup>

$Q$  = discharge from turbines, m<sup>3</sup>/sec

$H$  = effective head, m

$\eta$  = efficiency, %

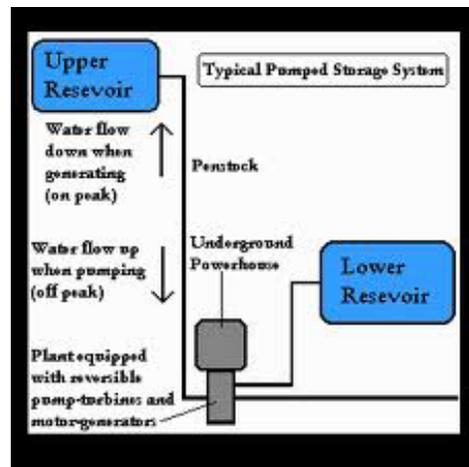


Figure 1 PHESS

### UPHESS: UNDER GROUND PUMPED HYDRO ELECTRIC ENERGY STORAGE SYSTEM

An UPHESS facility has the same operating principle as PHESS: two reservoirs with a large hydraulic head between them. The only major difference between the two designs is the locations of their respective reservoirs. In conventional PHESS, suitable geological formations must be identified to build the facility. UPHESS can provide the same services as PHESS: load-leveling, frequency regulation, and peak generation. However, as UPHESS does not need to be built at a suitable geological formation, it can be constructed anywhere with an area large enough for the upper reservoir. Consequently, it can be placed in ideal locations to function with wind farms, the power grid, specific areas of electrical irregularities etc. The flexibility of UPHESS makes it a more attractive option for energy storage than conventional PHESS, but its technical immaturity needs to be addressed.

### CAESS: COMPRESSED AIR ENERGY STORAGE SYSTEM

A CAESS facility consists of a power train motor that drives a compressor, high pressure turbine (HPT), a low pressure turbine (LPT), and a generator. In conventional Gas Turbines (GT), 66% of the gas used is required to compress the air at the time of generation. Therefore, CAESS pre-compresses the air using off-peak electrical power and it is taken from the grid to drive a motor and stores it in large storage reservoirs. When The GT is producing electricity during peak hours, the compressed air is released from the storage facility and used in the GT cycle. As a result, instead of using expensive gas to compress the air, cheaper off-peak base load electricity is used. Figure 2 explains about CAESS.

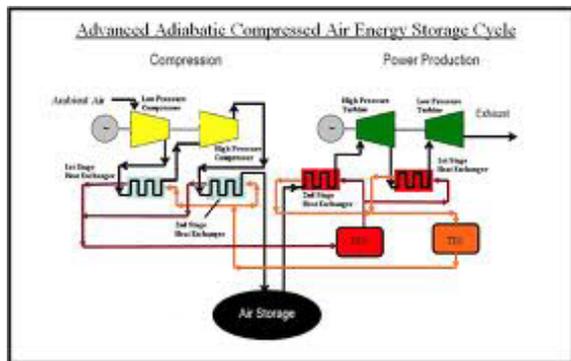


Figure 2 CAESS

However, when the air is released from the cavern it must be mixed with a small amount of gas before entering the turbine. If there was no gas added, the temperature and pressure of the air would be problematic. If the pressure using air alone was high enough to achieve a significant power output, the temperature of the air would be far too low for the materials and connections to tolerate [3]. CAESS is the only very large scale storage technique other than PHESS. CAESS has a fast reaction time with plants usually able to go from 0% to 100% in less than ten minutes, 10% to 100% in approximately four minutes and from 50% to 100% in less than 15 seconds. As a result, it is ideal for acting as a large sink for bulk energy supply and demand and also, it is able to undertake frequent start-ups and shutdowns. Furthermore, traditional GT suffer a 10% efficiency reduction for a 5°C rise in ambient temperatures due a reduction in the air density. CAESS use compressed air so they do not suffer from this effect. Also, traditional gas turbines suffer from excessive heat when operating on partial load, while CAESS facilities do not. These flexibilities mean that CAESS can be used for ancillary services such as frequency regulation, load flowing, and voltage control [4].

**BESS: BATTERY ENERGY STORAGE SYSTEM**

There are three important types of large-scale BES. These are: 1. Lead-Acid (LA), 2. Nickel-Cadmium (NiCd), 3. Sodium-Sulphur. These operate in the same way as conventional batteries, except on a large scale i.e. two electrodes are immersed in an electrolyte, which allows a chemical reaction to take place so current can be produced when required. There are two types of lead-acid (LA) batteries; flooded lead-acid (FLA) and valve-regulated lead-acid (VRLA). FLA batteries are made up of two electrodes that are constructed using lead plates which are immersed in a mixture of water (65%) and Sulphuric acid (35%). VRLA batteries have the same operating principle as FLA batteries, but they are sealed with a pressure-regulating valve. This eliminates air from entering the cells and also prevents venting of the hydrogen. VRLA batteries have lower maintenance costs, weight less and occupy less space. LA batteries can respond within milliseconds at full power. The average DC-DC efficiency of a LA battery is 75% to 85% during normal operation, with a life of approximately 5 years or 250-1,000 charge/discharge cycles, depending on the depth of discharge [4].

A Ni Cd battery is made up of a positive electrode with nickel oxy-hydroxide as the active material and a negative electrode composed of metallic cadmium. These are separated by a nylon divider. The electrolyte, which undergoes no significant change during operation, is aqueous potassium hydroxide. During discharge, the nickel oxy hydroxide combines with water and produces nickel hydroxide and a hydroxide ion. Cadmium hydroxide is produced at the negative electrode. To charge the battery the process can be reversed. However, during charging, oxygen can be produced at the positive electrode and hydrogen can be produced at the negative electrode. As a result some venting and water addition is required, but much less than required for a LA battery.

The DC-DC efficiency of a NiCd battery is 60%-70% during normal operation although the life of these batteries is relatively high as 10 to 15 years, depending on the application. NiCd batteries with a pocket-plate design have a life of 1,000 charge/discharge cycles, and batteries with sintered electrodes have a life of 3,500 charge/discharge cycles. NiCd batteries can respond at full power within milliseconds. At small DoD rates (approximately 10%) NiCd batteries have a much longer cycle life (50,000 cycles) than other batteries such as LA batteries.

NaS batteries have three times the energy Density of LA, a longer life span, and lower maintenance. These batteries are made up of a cylindrical electrochemical cell that contains a molten-sodium negative electrode and a molten-sulphur positive electrode. The electrolyte used is solid β-alumina. During discharging, sodium ions pass through the β-alumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulfide. During charging, the reaction is reversed so that the sodium polysulfide decomposes, and the sodium ions are converted to sodium at the positive electrode. In order to keep the sodium and sulphur molten in the battery, and to obtain adequate conductivity in the electrolyte, they are housed in a thermally-insulated enclosure that must keep it above 270°C, usually at 320°C to 340°C.

NaS is able to provide power in a single, continuous discharge or else in shorter larger pulses (up to five times higher than the continuous rating). It is also capable of pulsing in the middle of a long-term discharge. This flexibility makes it very advantageous for numerous applications such as energy management and power quality. NaS batteries have also been used for deferring transmission upgrades.

Table 1: Comparison of Large Scale Energy Storage System

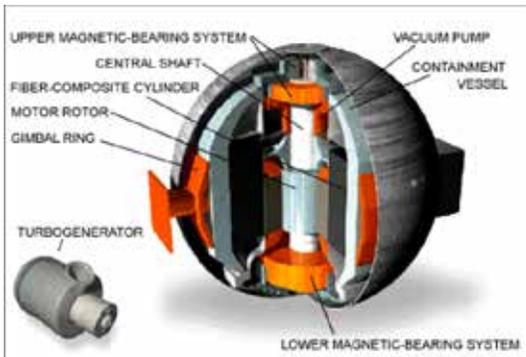
| Parameter            | PHESS | CAESS | BESS   |
|----------------------|-------|-------|--------|
| Efficiency           | 75%   | 70%   | 85%    |
| Modular              | No    | No    | Yes    |
| Energy Capacity      | 10GWh | 5GWh  | 50MWh  |
| Power (Maximum)      | 3 GW  | 1 GW  | 100 MW |
| Cost (Rs in Lacs/KW) | 1.05  | 0.4   | 0.95   |

Although capital costs and the presence of appropriate geography are critical decision factors, Pumped-hydro energy storage technique is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis. Moreover, it is the most widespread energy storage system in use on power networks.

**FESS: FLYWHEEL ENERGY STORAGE SYSTEM**

An FESS device is made up of a central shaft that holds a rotor and a flywheel. This central shaft rotates on two magnetic bearings to reduce friction. These are all contained within a vacuum to reduce aerodynamic drag losses. Flywheels store energy by accelerating the rotor/flywheel to a very high speed and maintaining the energy in the system as kinetic energy. Flywheels release energy by reversing the charging process so that the motor is then used as a generator. As the flywheel discharges, the rotor/flywheel slows down until eventually coming to a complete stop. The rotor dictates the amount of energy that the flywheel is capable of storing. Flywheels store power in direct relation to the mass of the rotor, but to the square of its surface speed. Consequently, the most efficient way to store energy in a flywheel is to make it spin faster, not by making it heavier. Figure 3 clears the idea of FESS. The energy density within a flywheel is defined as the energy per unit mass:

$E_{KINETIC} / mf = \frac{1}{2} V^2_{CIRCULAR} = \sigma / \rho$   
 Where:  
 $E_{KINETIC}$  = total kinetic energy - J  
 $m_f$  = mass of the flywheel - kg  
 $V_{CIRCULAR}$  = flywheel circular velocity - m/s  
 $\sigma$  = specific strength - material Nm/kg  
 $\rho$  = density of the material - kg/m<sup>3</sup>



**Figure 3 FESS**

The power and energy capacities are decoupled in flywheels. In order to obtain the required power capacity, support must be optimised for the motor/generator and the power electronics. These systems, referred to as 'Low-speed flywheels', usually have relatively low rotational speeds, approximately 10,000 rpm and a heavy rotor made from steel. They can provide up to 1650 kW, but for a very short time, up to 120 s.

Flywheels have an extremely fast dynamic response, a long life, require little maintenance, and are environmentally friendly. They have a predicted lifetime of approximately 20 years or tens of thousands of cycles. As the storage medium used in flywheels is mechanical, the unit can be discharged fully and repeatedly without any damage to the device. Consequently, flywheels are used for power quality enhancements such as UPS, capturing waste energy that is very useful in electric vehicle applications and finally, to dampen frequency variation, making FES very useful to smooth the irregular electrical output from wind turbines.

**SMES: SUPER MAGNETIC ENERGY STORAGE SYSTEM**

A SMES device is made up of a superconducting coil, a power conditioning system, a refrigerator and a vacuum to keep the coil at low temperature.

Energy is stored in the magnetic field created by the flow of direct current in the coil wire. In general, when current is passed through a wire, energy is dissipated as heat due to the resistance of the wire. However, if the wire used is made from a superconducting material such as lead, mercury or vanadium, zero resistance occurs, so energy can be stored with practically no losses. In order to obtain this superconducting state within a material, it must be kept at a very low temperature. There are two types of superconductors; low-temperature superconductors that must be cooled from 0 K to 7.2 K, and high-temperature superconductors that have a temperature range of 10 K to 150 K, but are usually in the 100±10K region. The energy stored within the coil is given:

$$EC = \frac{1}{2} LI^2$$

Where,  
 Ec = Energy Stored in Inductor, J  
 L = Inductance, H  
 I = Current, Amp

Therefore, material properties are extremely important as temperature, magnetic field, and current density are pivotal factors in the design of SMES. The overall efficiency of SMES is in the region of 90% to 99% [5]. SMES has very fast discharge times, but only for very short periods of time, usually taking less than one minute for a full discharge. Discharging is possible in milliseconds if it is economical to have a PCS that is capable of supporting this. Storage capacities for SMES can be anything up to 2 MW, although its cycling capability is its main attraction. SMES devices can run for thousands of charge/discharge cycles without any degradation to the magnet, giving it a life of 20+ years.

**SCES: SUPER CAPACITORS ENERGY STORAGE SYSTEM**

Capacitors consist of two parallel plates that are separated by

a dielectric insulator. The plates hold opposite charges which induces an electric field, in which energy can be stored. The energy within a capacitor is given by:

$$E = \frac{1}{2} CV^2.$$

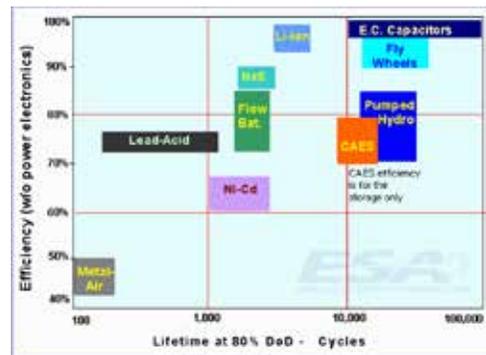
Where,  
 E = Energy Stored, J  
 C = Capacitance, F  
 V = Voltage, V

Super capacitors are created by using thin film polymers for the dielectric layer and carbon Nano-tube electrodes. They use polarised liquid layers between conducting ionic electrolyte and a conducting electrode to increase the capacitance. They can be connected in series or in parallel. SCES systems usually have energy densities of 20 MJ/m<sup>3</sup> to 70 MJ/m<sup>3</sup>, with an efficiency of 95% [2]. The main attraction of SCES is its fast charge and discharge, combined with its extremely long life of approximately 1 x 10<sup>6</sup> cycles. This makes it a very attractive replacement for a number of small-scale (<250 kW) power quality applications. In comparison to batteries, super capacitors have a longer life, do not suffer from memory effect, show minimal degradation due to deep discharge, do not heat up, and produce no hazardous effect [1]. As a result, although the energy density is smaller, SCES is a very attractive option for some applications such as hybrid cars, cellular phones, and load leveling tasks. SCES is primarily used where pulsed power is needed in the millisecond to second time range, with discharge times up to one minute [2].

**COMMENTS:**

No ESS has the ideal characteristics required for the grid integration as well as for the electric vehicle. In relation to the other ESS, BESS, FESS, SCES will most likely be used in Electric Vehicles and Hybrid Electric Vehicles. Looking at the Indian needs of Energy for Transportations, it is uncertain about the hybrid energy storage system for the grid as well as electric vehicles.

**Chart: Comparison of ESS:**



**Table: Comparison of ESS:**

| Type of Storage System | P \$/kW  | E \$/kWh   | O & M \$/kW-Yr | Environmental effects | Safety               |
|------------------------|----------|------------|----------------|-----------------------|----------------------|
| PHESS                  | 600-2000 | 0-20       | 3.8            | Reservoir             | Exclusion Area       |
| CAESS                  | 425-517  | 50         | 3.77           | Gas Emission          | Pressure Vessels     |
| BESS                   | 200-1800 | 175-1500   | 1.55           | Chemical Handling     | Hazards of Chemicals |
| FESS                   | 300-350  | 200-25000  | 7.5            | -                     | Containment          |
| SCES                   | 300      | 82000      | 5.55           | -                     | -                    |
| SMES                   | 300      | 2000-72000 | 8-26           | -                     | Magnetic Field       |

## REFERENCE

- [1] Cheung KY, Cheung ST, Navin De Silva RG, Juvonen MP, Singh R, Woo JJ. Large-Scale Energy Storage Systems, Imperial College London, 2003.
- [2] Gonzalez A, Ó'Gallachóir B, McKeogh E, Lynch K. Study of Electricity Storage Technologies and Their Potential to Address Wind Energy Intermittency in Ireland, Sustainable Energy Ireland, 2004. [3] White paper 65 "Comparison of Energy Storage Systems" by Stephen McCluer and Jean-Francois Christin. [4] Baxter R. Energy Storage - A Nontechnical Guide. Oklahoma: PennWell Corporation, 2006. [5] Sandia National Laboratories. Energy Storage Systems, Sandia National Laboratories, 2003 - its Web Site. [6] "Energy Technology" By S. Rao [7] Comparison of Energy Storage Alternatives using Fuzzy TOSIS Method by Ronay Ak, Canan Ađlan, World Congress of Engineering, London, 2011. [8] David Connolly, Martin Leuhy, A Review of Energy Storage Technology, University of Limerock, Version 4, 2010. [9] Uddin, N., Preliminary design of an underground reservoir for pumped storage. Geotechnical and Geological Engineering, pp. 331-355, 2003. [10] Compressed Air Energy Storage (CAES) in Salt Caverns, Argonne National Laboratory, 28th October 2007. [11] Lund, H. & Salgi, G., The role of compressed air energy storage (CAES) in future sustainable energy systems. Energy Conversion and Management, 50(5), pp. 1172-1179, 2009. [12] Wind plus compressed air equals efficient energy storage in Iowa proposal, Energy Services, 30th October 2007. [13] Schoenung, S. Characteristics and Technologies for Long vs. Short-Term Energy Storage. Sandia National Laboratories Report SAND2001-0765, 2001. [14] Gordon, S. & Falcone, P. The Emerging Roles of Energy Storage in a Competitive Power Market: Summary of a DOE Workshop. Sandia National Laboratories Report: SAND95-8247 UC-406, 1995. [15] Waldmar Jungner, Battery Facts, 7th October 2010. [16] Nickel Cadmium Fibre Plate Batteries: Dimensional and Electrical Data, Storage Battery Systems Inc., 2010. [17] Utility Will Use Batteries to Store Wind Power, The New York Times, 26th October 2007. [18] Norris, B. L., Ball, G. J., Lex, P. & Scaini, V. Grid-Connected Solar Energy Storage Using The Zinc-Bromine Flow Battery. ZBB Energy Corporation Technical Paper, 2002. [19] Flywheels - A look to the future, 27th October 2007, www.upei.ca. [20] Krom, L. Renewable Hydrogen for Transportation Study. Wisconsin Energy Bureau Contract 87052, 1998. [21] Lund, H. & Mathiesen, B. V., Energy system analysis of 100% renewable energy systems--The case of Denmark in years 2030 and 2050. Energy, 34(5), pp. 524-531, 2009. [22] Lund, H. & Kempton, W., Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy, 36(9), pp. 3578-3587, 2008. [23] Hybrid Electric and Battery Electric Vehicles: Technology, Costs and Benefits, Sustainable Energy Ireland, 2007. [24] EnergyPLAN: Advanced Energy System Analysis Computer Model, Aalborg University, 14th September 2010. [25] Connolly, D., Lund, H., Mathiesen, B. V. & Leahy, M., The first step towards a 100% renewable energysystem for Ireland. Applied Energy, In Press, Corrected Proof, 2010. [26] Technology and Comparisons, Electricity Storage Association (ESA), 5th November 2007, [27] Bakos, G. C., Feasibility study of a hybrid wind/hydro power-system for low-cost electricity Production. Applied Energy, 72(3-4), pp. 599-608, 2002.