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Energy Storage: A Review

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Abstract: Energy supply is the task that provides a reliable energy service to consumers throughout the year . Efficient and economic energy storage, if implemented in the current power infrastructure on a large scale, could bring about some of the greatest changes in the power industry in decades. Additionally, energy storage would improve the reliability and dynamic stability of the power system by providing stable, abundant energy reserves that require little ramp time and are less susceptible to varying fuel prices or shortages. Energy storage can shift the higher peak load to off-peak hours in order to level the generation requirement, allowing generators to run more efficiently at a stable power level, potentially decreasing the average cost of electricity. Additionally, increased energy storage capacity can avoid generation capacity, decrease transmission congestion, and help enable distributed generation such as residential solar and wind systems. In this paper energy storage methods are discussed in such a way to provide a detailed overview of how each of the energy storage devices work so that the reader is able to get a better feel for the potential benefits and drawbacks of each device.

***K*eywords:** CHP, TES, CAES

INTRODUCTION

Energy storage system plays very important role in our life to meet the requirement of energy conservation It is the most promising technology to reduce fuel consumption in the transport sector.The Reliable and affordable electricity storage is a prerequisite for using renewable energy in remote locations, the integration into the electricity system and the development of a future decentralized energy supply system. Energy storage therefore has a vital role in the effort to combine a future, sustainable energy supply with the standard of technical services. A delayed response to a power requirement and inadequate or excessive power levels are unacceptable to industrial, commercial and private consumers and can lead to application failures. Energy storage systems match the requirements of applications to the energy supply. [1]Power stations, compressors, heating systems etc all have different performance characteristics concerning their response time to changing demand, their lead times for starting up or shutting down and their most efficient point of operation. Without energy storage the timely availability of energy is compromised and operation of energy generation and conversion devices at low efficiency levels has to be accepted. The decision to use an energy storage system depends on the demands of the application and the cost of competing solutions in renewable energy systems, for instance, the use of fossil fuel based generation and grid connection are competing solution. Flourishing use of electric grid needs permanent online balancing of supply and demand including grid losses. Correctly chosen electricity storage technology, will smooth out this surges and allow electricity to be dispatched at a later time. The simplest definition of a storage device is one that is specifically designed to accept electrical energy from the grid, convert it into an energy form suitable for storage, subsequently convert it back into electricity and, apart from any losses due to inefficiencies, return it to the grid [1]. Energy storages have wide spectrum of using in the different scope of applications. Mainly, it is caused by their special storage capacities and energy power that can be received from a various range of devices. Figure 1 shows topology of energy storages with classifications by sectors. PHES abbreviation means Pumped Hydroelectric Energy Storage, UPHES - Underground Pumped Hydroelectric Energy Storage, CAES - Compressed Air Energy Storage, TES - thermal energy storage, CHP - Combined Heat and Power and CSP - Concentrated Solar Power energy storages. These storages are not described in this paper due to their specific power rates and installation difficulties for small households. Other abbreviations from figure will be described later. Despite that energy storages have own assorted properties and features, all of them have general base parameters also. The most significant is energy storage capacity - the total of electrical energy that storage can accumulate, official units of measure are megawatt-hours (MWh) or kilowatt-hours (kWh) for small applications. The second significant parameter is power capacity - the highest immediate productivity that an energy storage system can supply, the units of measure are megawatts (MW) or kilowatts (kW). The efficiency parameter should be considered at calculations of a recoupment of system during projecting - shows the sum of electricity on output with difference in the percents from device charge electricity. Power quality property is ability of energy storage to transfer to demand the energy with good quality without harmonics, spikes or other problems. Round-Trip efficiency parameter same as efficiency property, same indicates in the percents the quantity of electricity which can be recovered from the electricity used to charge and discharge the device. And the last main property is response time which shows the time which goes from request and energy storage power

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output response. Back to consumption and supplier relation, there are two main load management features. Load levelling: applying off-peak electricity to charge the energy storage system and after that ENERGY STORAGES 4 / 50 permit it to discharge during peak demand (energy storage devices can be charged during off-peak hours and then used to provide electricity when it is the most expensive, during short peak production periods). Therefore, the overall power production requirements become flatter and thus cheaper base load power production can be increased. Another is load following: energy storage device works as a sink when power falls on demand below production level and works as a source when power required is above production levels [2]. Due to the complicated design of some energy storage systems it is important to bear in mind that initial investments in developing and installation usually have higher costs than their alternatives. As a result, on the stage of calculation, the life cycle costing (LCC) analysis could be applied, in which all costs associated with the alternative approaches are defined over a certain time period, usually 10 or 30 years. These costs are discounted to a net present value, so that they can be directly compared. Fig. 1 The main groups of energy storage and their abbreviations Task to make a fair description and comparison among the energy storage technologies, requires grouping them together with based on the size of power and storage capacity that they have. We can theoretically create three groups: energy storage capacities with either medium power 5-100 MWh or medium storage capacities 5-100 MWh; storages with average power 1-50 MW and storage capacities 5-100 MWh; finally storages with large power >50 MW and storage >100 MWh capacities.

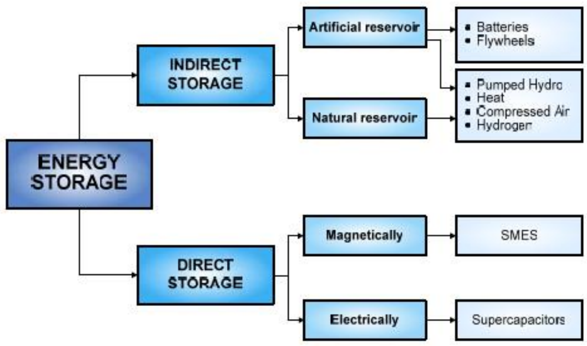

Fig: classification of energy storage system

Mechanical Energy Storage

- Pumped Hydroelectric Storage: Potential energy of water at different elevations.
- Compressed Air Energy Storage: Kinetic energy stored in compressed air.
- Flywheel Energy Storage: Kinetic energy stored in a rotating disk.

Electrical Energy Storage

- Electrochemical Capacitors (Supercapacitors): Electrostatic energy stored in an electric field (electrostatic energy).
- Superconducting Magnetic Energy Storage: Energy stored in a magnetic field (magnetic energy).

Chemical Energy Storage

- Lead Acid Batteries: Conventional secondary battery.
- Nickel-electrode Batteries: Conventional secondary battery.
- Lithium-ion Batteries: Secondary battery.
- Sodium-sulfur Batteries: Molten salt battery.
- Sodium Nickel Chloride Batteries (ZEBRA): Molten salt battery

Pumped Hydroelectric Storage

The oldest (1929) and most prominent energy storage technology to date has been pumped hydroelectric storage of which there are 20.36 GW of installed capacity in the United States alone [9] across 39 sites with capacities ranging from 50 MW to 2,100 MW [10]. Its simplicity of design, relatively low cost, and similarity in operation to hydroelectric power has made it the industry standard for storage for a century. These systems can quickly ramp up to full load: 10 seconds if the turbine spinning, and 1 minute from standstill [8]. However, they require very specific geographic features that limit unit siting. These systems have high capital cost but very low maintenance costs, and also face criticism due to their significant impact on local wildlife and ecosystems. New designs, however, may be opening the door for additional siting opportunities in the near future. How it Works As shown in Figure 3.1, PHS consists of two reservoirs with a height differential and a pipe (or penstock) connecting them. To store energy, electricity turns a motor which pumps water from the lower reservoir, up the pipe, to the upper reservoir. To produce energy, water is allowed to flow from the upper reservoir down the pipe through a turbine and into the lower reservoir. The turbine is connected to a generator and as the turbine turns so does the generator, producing electricity. Today, the motor and generator are typically one in the same, since a motor can also act as a generator (in one case it is turned and electricity is produced, in the other electricity is sent in, causing it to turn). There are two factors that control the power and energy rating of the system: the height difference between the reservoirs (known as the “head”, and the volume of the reservoirs (the “flow”) [5]. The larger the volume of water available and the greater the height, the more energy can be stored.

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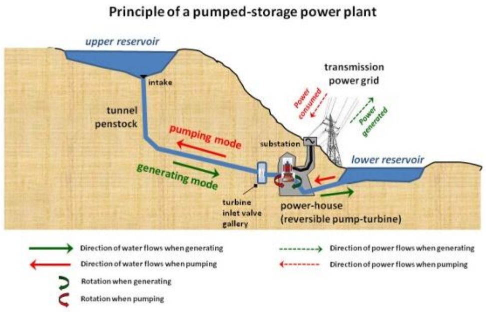
The greater the flow rate through the pipes, the more power can be produced. This comes from the basic physical principle that potential energy due to gravity is proportional to mass times height, with the constant of proportionality being acceleration due to gravity: E = mgh. Since power is the time rate of energy, or the derivative of energy, and since gravity and height are constant with time, power can be defined as: P = dE* dt = dm*dt*gh. So to increase the energy capacity of the system, increase the volume of water and height differential, to increase the power capacity increase the flow rate of water and height differential.



Battery Energy Storage (BES)

There are three important types of large-scale BES.

These are:

1. Lead-Acid (LA)

2. Nickel-Cadmium (NiCd)

3. Sodium-Sulphur (NaS)

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.

Lead Acid (LA) battery

This is the most common energy storage device in use at present. Its success is due to its maturity (research has been ongoing for an estimated 140 years), relatively low cost, long lifespan, fast response, and low self discharge rate. These batteries are can be used for both short-term applications (seconds) and longterm applications (up to 8 hours). There are two types of lead-acid (LA) batteries; flooded lead-acid (FLA) and valve-regulated leadacid (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 pressureregulating valve. This eliminates air from entering the cells and also prevents venting of the hydrogen. VRLA batteries have lower maintenance costs, weigh less and occupy less space. However, these advantages are coupled with higher initial costs and shorter lifetime. 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. Applications FLA batteries have 2 primary applications: 1. Starting and ignition, short bursts of strong power e.g. car engine batteries 2. Deep cycle, low steady power over a long time

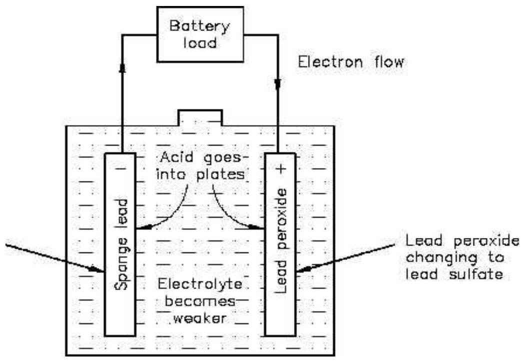


Fig: Lead Acid battery.89

Features Advantages: High power capacity; low volume energy density; low capital cost; long lifetime.

Disadvantages: Low efficiency; potential adverse environmental impact [14].

Nickel Cadmium (NiCd) battery**:** A NiCd battery is made up of a positive with nickel oxyhydroxide 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 changes during operation, is aqueous potassium hydroxide. During discharge, the nickel oxyhydroxide 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 at 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

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3,500 charge/discharge cycles. NiCd batteries can respond at full power within milliseconds. Applications Sealed NiCd batteries are used commonly in commercial electronic products such as a remote control, where light weight, portability, and rechargeable power are important. Vented NiCd batteries are used in aircraft and diesel engine starters, where large energy per weight and volume are critical. NiCd batteries are ideal for protecting power quality against voltage sags and providing standby power in harsh conditions. Recently, NiCd batteries have become popular as storage for solar generation because they can withstand high temperatures.

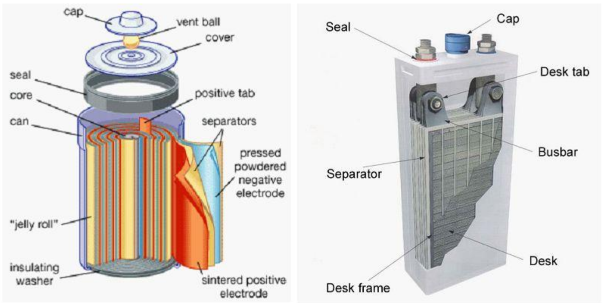


Fig: Nickel Cadmium Battery.

Features Advantages: Short access time; high energy density; high efficiency Disadvantages: Cycling and safety control required; environmental concerns [4]

Sodium Sulphur (NaS) Battery: 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 βalumina. During discharging, sodium ions pass through the βalumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulfide, see figure below. 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. A typical NaS module is 50 kW at 360 kWh or 50 kW at 430 kWh. The average round-trip energy efficiency of a NaS battery is 86% to 89%. The cycle life is much better than for LA or NiCd batteries. Applications One of the greatest characteristics of NaS batteries is its ability 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.

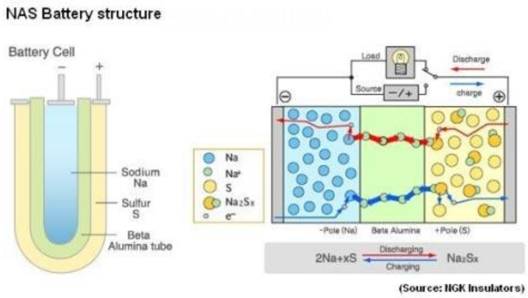
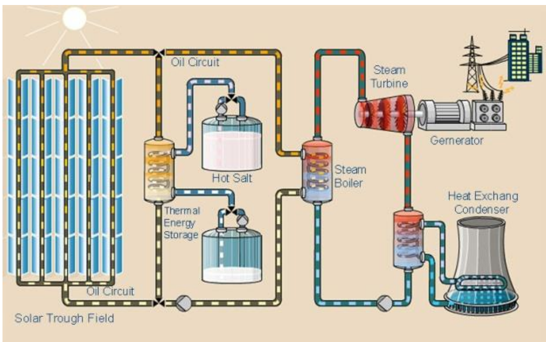


Fig: Sodium Sulphur Battery.

Features Advantages: Very high energy and power capacity; high energy density; high efficiency; long life time.

Thermal Energy Storage System (TESS): The thermal energy storage system can also be used very effectively to increase the flexibility within an energy system. As mentioned previously in this chapter, by integrating various sectors of an energysystem, increased windpenetrations can be achieved due to the additional flexibility created. Unlike the hydrogen energy storage system which enabled interactions between the electricity, heat and transport sectors, thermal energy storage only combines the electricity and heat sectors with one another. By introducing district heating into an energy system, then electricity and heat can be provided from the same facility to the energy system using Combined Heat and Power (CHP) plants.



This brings additional flexibility to the system which enables larger penetrations of intermittent renewable energy sources. To illustrate the flexibility induced by thermal energy storage on such a system, a snapshot of the power during different scenarios is presented below. The system in question contains a CHP plant, wind turbines, a thermal storage, a hotwater demand, and an electrical demand as illustrated in Figure 519. During times of low windpower, a lot of electricity must be generated by the CHP plants to accommodate for the shortfall power

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production. As a result, a lot of hot water is also being produced from the CHP plant as seen in Figure 519a. The high production of hot water means that production is now greater than demand, and consequently, hot water is sent to the thermal storage. Conversely, at times of high windpower, the CHP plants produce very little electricity and hot water. Therefore, there is now a shortage in of hot water so the thermal storage is used to supply the shortfall, as seen in Figure 519b. This system has been put into practice in Denmark which has the highest wind penetration in the world. Also, Lund has outlined a roadmap for Denmark to use this setup in achieving a 100% renewable energy system [6].

COMPRESSD AIR ENERGY STORAGE (CAES): In compressed air energy storage systems, off-peak grid power is used to pump air underground until it reaches a high pressure. It remains underground in a geologic formation until energy is needed, then it is released and heated, and passing through and turning a turbine, which generates power. CAES systems are essentially high efficiency combustion turbine plants. In CAES systems, the air is already compressed, and therefore uses significantly less fuel. Because of their similarity to standard combustion turbine systems, they are easily integrable into existing power networks. With a ramp rate similar and slightly faster than traditional gas plants, these systems are ideal for meeting peak load. WORKING - The storage process begins as air is passed through a compressor. The motor for the compressor can be either a separate device or the generator operating as a motor. Cooling the air occurs between each stage (intercoolers) as well as after the compression (after cooler), which reduces the volume of the gas to be stored and removes the heat generated during the compression. Once the air is compressed and stored, it may be released when needed to produce power. [7]During discharge, the air is mixed with fuel (such as gas, oil, or hydrogen) and combusted, and is then passed through the turbine stages, at which point the air expands, releasing energy, causing the turbine to spin and thereby driving the generator to produce electricity.

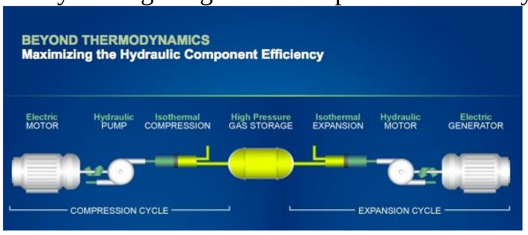

Fig: Compressed Air Energy Storage

OPERATION **-** These systems startup within 5-12 minutes with a ramp rate of 30% of maximum load per minute. MAINTENANCE - The maintenance requirements are similar to that of a standard combustion turbine natural gas plant of a similar size. ENVIRONMENTAL IMPACT - Since this technology produces emissions from combustion, there is an environmental concern especially compared to emissions free devices. However, the level of nitro produced is below 5ppm. APPLICATION - A compressed air engine uses the expansion of compressed air to drive the pistons of an engine, turn the axle, or to drive a turbine. Other applications are cars wind power. [8]

Flywheel Energy Storage (FES): Flywheels have been in existence for centuries, however, over the past few years they have been considered as forms of bulk energy storage. A simple form of kinetic energy storage, these systems are extremely rapid in their response time and, with recent developments in bearing design, have been able to achieve high efficiencies for short durations of storage. Their disadvantages are that they have a high rate of self discharge due to frictional losses, and their relatively high initial costs. [1]

WORKING - Flywheels store energy in rotating discs as kinetic energy in the form of angular momentum. It works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy; adding energy to the system correspondingly results in an increase in the speed of the flywheel. To "charge" this device, energy is used to power a motor which spins the disc, and the disc remains spinning until the energy is needed. At that point the disc is allowed to turn a generator, which produces electricity. The speed of the flywheel increases during charge (adding energy) and decreases during discharge (losing energy). The kinetic energy of a spinning Mass: Where, I is the moment of inertia and for a solid rotating disc is defined as $I = 1/2mr^2$ (m is mass of The disc, and r is the radius of the disc), and ω is the rotational velocity. This implies that by increasing the maximum speed of the disc the energy capacity is more greatly increased than by increasing the mass of the disc.

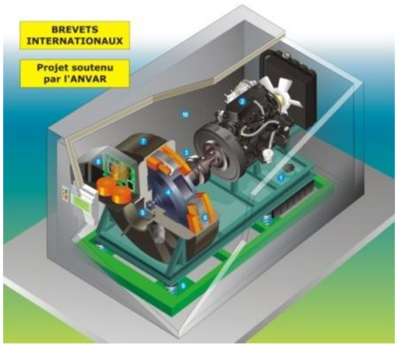

Fig: Flywheel energy storage system

Super Conducting Magnetic Energy Storage: This is the only energy storage technology that stores flowing electric current, this flowing current generates a magnetic field in

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which the energy is stored. These devices are extremely efficient, fast-responding, scalable to large sizes, and environmentally friendly, however, costly. They store electrical energy directly in a magnetic field with essentially no losses due to superconducting coils, aside from losses to keep the coil cool.

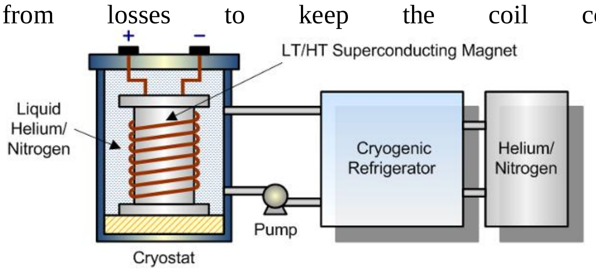

Fig: Super Conducting Magnetic Energy Storage.

WORKING - Direct current that is carries through superconducting material experience no resistive loss. The electric Current that flows in the coil induces a magnetic field in which the energy is stored. The current continues to loop around the coil indefinitely until it is needed and is discharged. However, there is a price for the superconducting Property, and it is that the superconducting coil must be super-cooled to very low temperatures, some in the range of 50-77k, others such as alloys of niobium and titanium around 4.5k . These devices require a cryogenic cooling System using liquid nitrogen or helium, and this system presents, in itself, a parasitic energy loss. The amount of energy these devices store depends on both the size of the coil and its geometry (which determines the Inductance(L) of the coil). Since a coil is an inductor, it follows physical principles that it stores energy based on the Square of the current(i) so the amount of current flowing in the coil can be incredibly large. At a magnetic Flux density of 5 (tesla), practical superconductors can carry currents of 300,000A/cm^2 . [8]

VARIATIONS - The major design variations are in the power and energy capacity of the unit and the geometry of the superconducting coil, none of which deviate by much from the functionality described above. Sometimes smaller capacity SMES Systems (less than 0.1 mwh) are referred to as micro-SMES. [11]

SUPER CAPACITORS: Conventional electrostatic capacitors, this is the simplest form of capacitor, and works by storing energy in an electric field. Two plates (electrodes) are placed very close together, but not touching, with either air other nonconductive material (known as a dielectric) in between the plates. A power source is then connected across the plates which place a voltage across the plates, with one side being positively charged and the other negatively charged. This desire of the electron to equalize the charge is their potential to do work, or the stored energy (stored in the electric field). The amount of energy stored in a capacitor is E=1/2(cv^2). Electrolytic capacitors, these devices operate essentially the same way as the electrostatic capacitor, except they use an electrolyte as one of the two plates, which means a larger capacitance per unit volume. Electrochemical capacitors the design of "supercapacitors" is essentially a hybrid between batteries and capacitors. They have two electrode plates and an electrolyte in between (like batteries) and when a power source is connected, ions make their way to the electrodes with opposite charges due to the electric field (since oppositely charged objects attract). The difference is that a chemical reaction does not occur; merely the ions migrate; so the storage mechanism is still the electric field. Therefore, unlike batteries that would wear out after being cycled due to numerous chemical reactions, the lifetime of these devices is not significantly impacted by cycling. Also, the electrodes are often made of carbon nanotubes, which, under a microscope, appear as masses of tangled string. This significantly increases the surface area of the electrodes, increasing the storage capacity of these devices significantly. In some devices, every square centimeter of electrode consists of one to two thousand square meters of surface area. [3]

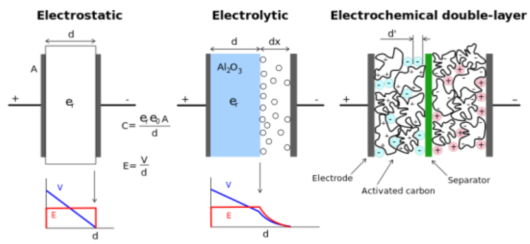

Fig: Supper capacitor

Hydrogen Energy Storage System (HESS): The HESS is the one of the most immature but also one of the most promising energy storage techniques available. As an energy storage system, HESS acts as a bridge between all three major sectors of an energy system: the electricity, heat and transport sectors. It is the only energy storage system that allows this level of interaction between these sectors and hence it is becoming a very attractive option for integrating large quantities of intermittent wind energy [12][13]. There are three stages in HESS:

1. Create hydrogen.

2. Store hydrogen.

3. Use hydrogen (for required application).

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Hydrogen has a very high enthalpy of 120MJ/kg, which is about 3 times that of Gasoline. Therefore, hydrogen is a good candidate as an energy carrier and methods for its storage have been investigated intensively. Five basic methods are proposed in the literature for hydrogen storage: compressed and stored in a pressure tank; cooled to a liquid state and kept cold in an insulated tank; physisorpted in carbon; metal hydrides and complex compounds. Metal hydrides and complex compounds occupy a smaller volume to store the same amount of hydrogen; however, this method is not suitable for this application due to its high ad/absorption temperature. Both liquid hydrogen and compressed gas at high pressure were better candidates for suitable methods for this project, however, liquid hydrogen requires more expensive equipments and very low temperature.

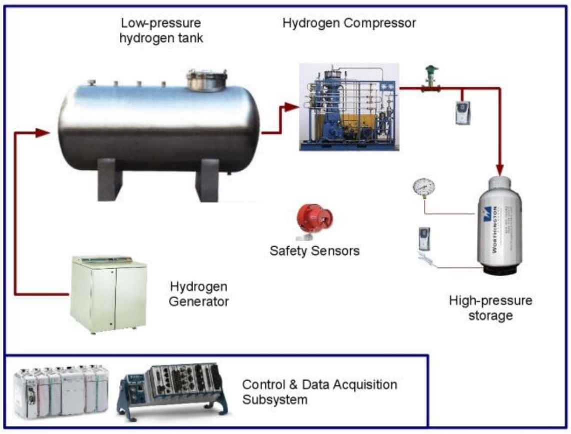

Fig: Hydrogen Energy Storage System

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