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# An Overview on Energy Storage Options for Renewable Energy Systems

**Ajay Sharma[1], Mr. Vishal Sharma[2], Jai Praksh Saini[3], Kailash Prashad Bairawa[4]**
[1]M.Tech. Student, [2]Assistant Professor, Jagannath University, Jaipur, Rajasthan, India
sharma.ajay792@gmail.com

## Abstracts

Developing technology to store electrical energy so it can be available to meet demand whenever needed would represent a major breakthrough in electricity distribution. Helping to try and meet this goal, electricity storage devices can manage the amount of power required to supply customers at times when need is greatest, which is during peak load. This paper focuses on four storage technologies that can be used as storage for wind energy conversion system. For each storage technology, the advantages and disadvantages, costs involved, the efficiency, the energy density and some major break-through in technology are discussed.

**Keywords**: storage technologies, flywheel, pumped hydro storage, compressed air energy storage, hydrogen storage, fuel cell.

## Introduction

Today, the world is consuming more energy than it used to in the past. The new generations are developing new technologies and gadgets that will make their life more sophisticated which would require greater energy usage. There is also a rising concern about the environmental pollution and high oil prices. More awareness is now being created by government and also non-governmental organizations about the prevention of environmental pollutions and in addition incentives are being given for production of electrical energy using non-conventional fuels. Due to these reasons there has always been research and development in finding new sources of energy apart from the conventional fuels.

The new sources of energy that were found were mostly renewable energy. Renewable energy offers the planet Earth a chance to reduce carbon emissions, clean the air, and put our civilization on a more sustainable footing. It also offers countries around the world the chance to improve their energy security and spur economic development [1]. There is always research and development being carried out in renewable energy technology to improve the efficiency, reliability, safety and price of each.

According to [2] in 2006, about 18% of global final energy consumption came from renewables. Renewable electricity generation capacity reached an estimated 240 gigawatts (GW) worldwide in 2007, an increase of 50 % over 2004 [1]. The largest component of renewables generation capacity is wind power, which increased by 28 % worldwide in 2007 to reach an estimated 95 GW and then topped 100GW by April 2008 [3].

To make a renewable energy system reliable, it means that it should be able to supply electrical energy for all 24 hours a day, 7 days a week and all year round. It should be able to meet energy demand during the peak times in a day or seasons. In order for this to happen there ought to be a very good energy storage system. Also energy storage technology can play important role in maintaining system reliability and power quality. Different renewable energy sources have different optimum energy storage system.

This paper presents a brief overview of wind energy and energy storage technology where for each technology there would be discussions on the advantages and disadvantages of each, the cost of storing wind energy in that particular storage system and what has been the major development in each of the storage technologies.

## Overview of wind energy

The largest increase in the installed capacity of renewable power generation was from wind energy in 2007 which showed a 28 % increase from 2006. Wind turbines convert the kinetic energy in the wind into mechanical powerand a generator is used is convert this mechanical energy into electrical energy to power homes, businesses, schools, etc. [4]-[6]. The total wind power, $P_w$, available to wind turbine is given by [7]-[18].

$$P_w = \tfrac{1}{2} \rho A v^3 \qquad (1)$$

where ρ is the density of air in kg/m$^3$, A is the swept area in m$^2$, v is the wind speed in m/s. The maximum wind

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power that can be harnessed by a wind turbine is 59.3 % (which is known as the Betz coefficient) of the total wind power. The electrical output power ($P_e$) from a wind turbine is given by [19].

$$P_e = C_{op} \tfrac{1}{2} \rho A v^3 \quad (2)$$

where $C_{op}$ is the overall power coefficient of the wind turbine which is the product of the mechanical efficiency ($\eta_m$) electrical efficiency ($\eta_e$) and the aerodynamic efficiency (Betz coefficient).

The strength of wind varies, and an average value for a given location does not alone indicate the amount of energy a wind turbine could produce there. In order to know the actual potential of wind energy that can be harnessed from a particular site the wind speed distribution for that particular site must be known. The wind speed distribution is the frequency of wind speeds. The frequency distribution curve of wind speed is convolved with a wind turbine power curve to yield the energy curve. The capacity factor (CF) is another issue that must be considered when estimating the annual wind energy yield. CF is the ratio of annual energy yield to the maximum energy annual energy yield.

$$CF = \frac{\text{annual energy yeild (kWh)}}{P_R\ (\text{kW}) \times 8760\ \text{hrs}} \quad (3)$$

Where $P_R$ is the rated power of the wind turbine

For proper and beneficial development of wind power at any site wind data analysis and accurate wind energy potential assessment are the key requirements. An accurate wind resource assessment (WRA) is an important and critical factor to be well understood for harnessing the power of the wind, since an error of 1% in wind speed measurement leads to a 3% error in energy output since energy is proportional to cube of wind speed [9], [20], [21]. It is well known that wind resource is seldom consistent and it varies with the time of the day, season of the year, height above the ground, type of terrain, and from year to year [8], [9], [17], [18], [22]. Once a proper WRA is done installation of wind turbine or wind farm is carried out.

## Energy storage systems

Managing the balance between electrical supply and demand is a complex problem which results in inherent monetary value of electricity changing by the hour. Also when new wind turbines/farms are connected to the grid, due to its variable and intermittent nature of the output it may cause grid network stability problems. To smooth out the variations in the grid, storage systems are needed. Authors in [23] proposed a concept of interline dynamic voltage restorer (IDVR) where dynamic voltage restorer (DVR) shares a common energy storage and when one of the DVR compensates for voltage sags, the other DVRs replenish the energy in the common dc-link dynamically. Melasani et al. [24] showed how active filters may be used compensate for current unbalances, high and low order harmonics, sub-harmonics and reactive power to result in sinusoidal, in-phase and symmetric line currents. The structure of active filters include one or more converters interfacing energy storage with the grid. In order to obtain complete and accurate compensation, fast response and high energy storage are needed. Fairley [25] discusses how power electronics and exotic energy storage devices make wind power steady enough to compete with conventional electricity sources. Researchers [26] showed that Quasi-direct converters (similar to indirect ac/dc/ac converters) require only a small energy storage in the dc link. This condition calls for instantaneous input/output balance, which must be provided by control. Advantages of Quasi-direct converters are that it is cheaper than conventional solutions, capable of high power density and has improved reliability. According to [27] an energy source power system stabilizer can regulate the real power output/input of energy storage system which is done by processing the frequency deviation signal. This can be applied to any energy storage system. Energy storage system helps marginally competitive resources such as many renewable overcome these limitations, and can also improve the economic efficiency of the entire grid system as a whole. Ribeiro et al. [28] have shown that energy storage devices can be integrated into power electronics converters to provide power system stability, enhance transmission capability and improve power quality. Adding energy storage to power electronics compensators not only enhances the performance of the device, but also provides the possibility of reducing the MVA ratings requirements of the front-end power electronics conversion system. Authors [29], [30] proposed multilevel power-electronics topologies which offer improved voltage quality, decreased switching frequencies, reduced power losses, and decreased stress on individual power-electronics devices. Cheng et. al. [31] showed that cascaded and diode-clamped multilevel converters provide superior performance to the traditional static synchronous compensators (STATCOM). Maharjan et al. [32] verified the viability of a 6.6-kV transformer less energy storage system. It was based on cascade multilevel pulse width modulation (PWM) converter with star configuration. The voltage balancing control was characterized by stable operation and easy expansion into a higher number of voltage levels. Authors [33] studied the application of STATCOM with energy storage for the elimination of sags and power oscillation. Fig. 1 [33] shows a power circuit of STATCOM and energy storage. It was found that for steady-state voltage control, the current rating of the converter is influenced by the control strategy used.

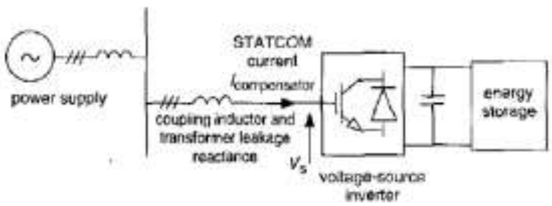


*Fig. 1. STATCOM-energy storage power circuit.*

There are a number of storage technologies and each of these is at various stages of research and development. The choice of storage technology for any particular renewable energy source application depends on the amount of rated power of the generator, the time involved, i.e., the period between storage and regeneration, cost factor and also on the efficiency of the overall system.

Ideally, energy storage technologies should:

- Be low capital, operating and maintenance cost;
- Be environmentally sustainable (i.e. low carbon emission) and flexible in operation;
- Be easy to implement;
- Have a long life-time;
- Have large energy density (i.e. total energy storage capacity) in kWh or MWh;
- Have a high efficiency; and
- Have a fast response.

Energy storage technologies could be highly beneficial to both the grid and the consumer. However, if these technologies are to be widely adopted, the technologies must also be economically profitable.

*A. Flywheel Energy Storage (FES)*

A flywheel, in essence is a mechanical battery, simply a mass rotating about its axis which is used to absorb electric energy from the source to store it as rotational kinetic energy and then deliver to a load at the appropriate time, in the form that meets the load needs.

FES has been implemented to store energy with some success [34]. However, flywheel has the potential of being one of the promising technologies for replacing conventional lead acid batteries as energy storage systems for a variety of applications, including automobiles, rural electrification systems, and stand-alone, remote power units commonly used in the telecommunications industry [35], [36].

The energy stored in the flywheel of mass, M (in kg) and radius, R (in m) is in the form of rotational kinetic energy, $E_{K_{rot}}$ ( in joules). The energy is proportional to the flywheel's mass and the square of its rotational speed.

$$E_{K_{rot}} = \frac{1}{2} I \omega^2 \tag{4}$$

where I is the inertia of flywheel in kgm$^2$ and ω is the rotational speed of flywheel in rad/s. The moment of inertia of the flywheel is given as

$$I = k M R^2 \tag{5}$$

where k is the inertia constant and it depends on the shape of the rotating object. For a flywheel loaded at rim such as a bicycle wheel or hollow cylinder rotating on its axis, k = 1, and for a solid disk of uniform thickness or a solid cylinder, k = ½.

In order to optimize the energy stored and at the same time decrease the cost of flywheel two options are can be worth to consider.

(i) Increase the rotational speed of the flywheel and
(ii) Increase the inertia (I) by increasing the radius while keeping the mass minimum for safety reasons. An option can be to have a hollow disc, i.e. in the shape of a ring.

However, the maximum energy that can be stored in a flywheel is also dependent on the material of the flywheel. Maximum energy storage ($E_{max}$) is achieved with a material of low density and a high tensile strength.

$$E_{max} = \frac{M S_y}{2\rho} \tag{6}$$

Where $S_y$ is the tensile strength in GPa of the flywheel material and ρ is the density of the flywheel material in kg/m$^3$.

It is important to note that the flywheel will not be spun up to its maximum speed since failure is likely to occur. According to Dinkins et. al [37] the actual energy storage will only be about 50 % of the maximum and is given by the formula

$$E_{act} = \frac{0.49 S_y M}{2\rho} \tag{7}$$

Modern high energy flywheels use composite rotors made with carbon-fiber materials. The rotors have a very

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high strength-to-density ratio, and rotate at speeds up to 100,000 rpm in a vacuum chamber to minimize aerodynamic losses [38]. The use of superconducting electromagnetic bearings can virtually eliminate energy losses through friction. Low speed flywheels with a speed up to 10 000 rpm are, therefore, contained in vessels filled with a helium to reduce the friction.

Carbon fiber materials have tensile strength ranging from 0.3 – 3 GPa and their density ranging from 1300 – 1900 kg/m$^3$ [39]. When a tensile strength of 3 GPa and density of 1800 kg/m$^3$ is taken and substituted in equation (7), the energy storage potential would be 113 Wh/kg.

Hence, it is observed that the higher the tensile strength and the lower density of the flywheel material, the higher will be the energy storage potential. The current price for building flywheels is estimated at $500/kWh with projected future costs as low as $100/kWh and its lifetime is approximately 40 years [37]. Flywheels can discharge at 100 kW for 15 seconds and recharge immediately at the same rate, providing 1-30 seconds of ride- through time [38].

*Advantages*: Flywheels store energy very efficiently ~95 % (high turn-around efficiency) and have the potential for very high specific power as compared with batteries. Flywheels have very high output potential and relatively long life (three times that of batteries) [40]. Flywheels are relatively unaffected by ambient temperature extremes. They are also less potentially damaging to the environment, being made of largely inert or benign materials [41].

*Disadvantages*: Current flywheels have low specific energy. Flywheels are best suited for high discharges, but can only provide power for a few seconds or minutes. There are safety concerns coupled with flywheels due to their high speed rotor and the possibility of it breaking loose and releasing all of its energy in an uncontrolled manner. Flywheels are a less mature technology than chemical batteries, and the current cost is too high to make them competitive in the market.

Recent advances in the mechanical properties of composites have rekindled interest in using the inertia of a spinning wheel to store energy. Research into exploiting this property of FES systems to get short, intense bursts of energy is ongoing with the most notable projects being a magnetic tank gun and a fusion ignition system. Authors in [42] proposed a hybrid controller, consisting of a model-based feed forward controller and a proportional–integral feedback compensator, for a solid-rotor synchronous reluctance motor/generator in a high-speed flywheel-based uninterruptible power supply application. Simulation and experimental results consisting of a flywheel energy storage system validates the performance of the controller. Cimuca et al. [34] investigated the control method and the energetic performances of a low-speed FES system with a classical squirrel-cage induction machine in the view of its association to a variable-speed wind generator. Authors in [43] showed how a series of voltage injection type FES system is used to mitigate voltage sags. Here the flywheel is coupled to an induction motor (Fig. 2) [43]. Indirect field oriented control with space vector PWM is used to control the induction machine and Sinusoidal PWM is used for controlling the power system side converter.

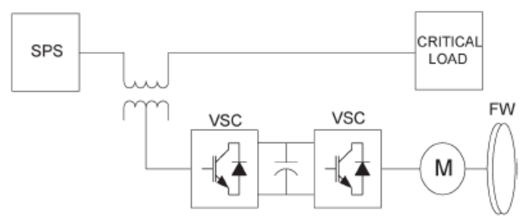


***Fig. 2. Basic circuit diagram for FES system.***

*B. Pumped Hydro Storage (PHS)*

PHS is the oldest and largest of the entire commercially available energy storage technologies, with facilities up to 1000 MW. Pumped hydropower is currently the most widely implemented storage technology in the U.S. and the world. In the United States, 38 plants provide 19 GW of power [44] and 24 GW in Japan. Pumped hydro capacity now equals 3 % of the total world generating capacity which shows evidence of its viability [45]. Pumped storage projects differ from conventional hydroelectric projects in that they normally pump water from a lower reservoir to an upper reservoir when demand for electricity is low.

Pumped hydro facilities consist of two large reservoirs; one located at a low level and the other situated at a higher elevation, Fig. 3. During off-peak hours, water is pumped from the lower to the upper reservoir, where it is stored. To generate electricity to supply peak demand, the water is then released back down to the lower reservoir, passing through hydraulic turbines and generating electrical power.

Pumped hydro is utilized for situations where a fast supply of power is needed (spinning reserve), for meeting sudden peaks in demand (load following), frequency regulation, and voltage control. Adjustable speed hydropower uses turbines and pumps that can operate at variable speeds depending upon the supply

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and demand for electricity. The pump turbines are able to operate over a range of rotation speeds (±10 % the speed of a conventional pump turbine) which allows them to vary the amount of electricity they generate by 70 % and the amount they store by 40 % [44]. They can regulate frequency in the pump mode and in the generation mode. Their power output can be changed in times of 10-30 ms.

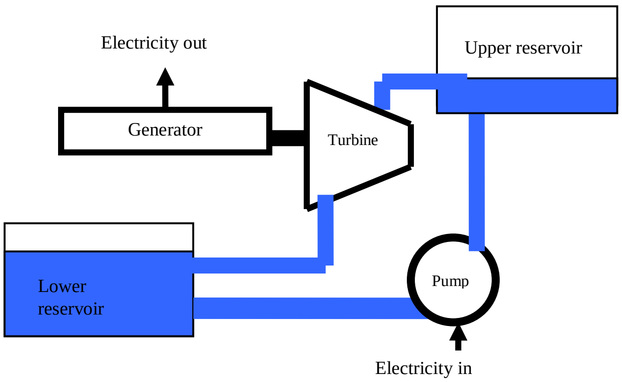


***Fig. 3. Pumped hydro storage block diagram.***

The electrical energy is stored as potential energy ($E_P$) in the upper reservoir.

$$E_P = m\,g\,h \tag{8}$$

where m is the mass of water in the upper reservoir in kg, g is the gravitational constant (9.8 $m/s^2$) and h is the change in elevation in m. Since the density of water (ρ) is ideally 1000 $kg/m^3$, the above equation (8) can be written as

$$E_P = \rho V\, g\, h \tag{9}$$

where V is the volume of water ($m^3$) in the upper reservoir. To optimize the energy stored in pumped hydro storage system the change in elevation must be large between the lower and upper reservoirs. Efficiency of PHS is 60 % in old units and 78 % in new units and its capacity factors ranges from 15 to 35 % [46]. The current cost for building a hydroelectric energy storage system is $2500 - $3000 per kW [37]. If the efficiency of PHS is taken as approximately 70 % and the elevation as 1000 m, then the energy density ($Wh/m^3$) would be 1.91 $kWh/m^3$.

According to [47] recent advances in pumped storage engineering have made it possible to build both reservoirs underground and avoid any natural water disturbance.

A new concept being developed is wind-pumped water storage which allows variations in wind power to be leveled by using the wind power to fill the upper reservoir and then generating grid power from the reservoir turbines. In [48], authors have applied the multi-pass dynamic programming to the solution of the short term hydrothermal coordination problem considering pumped storage and battery energy storage. This algorithm could quickly converge to an optimal generation schedule while achieving the minimum production cost of power system.

### *C. Compressed Air Energy Storage (CAES)*

CAES systems use off-peak power to pressurize air into an underground reservoir (salt cavern, abandoned hard rock mine, or aquifer) which is then released during peak day time hours to be used in a gas turbine for power production. Facilities are sized in the range of several hundred megawatts. In a gas turbine, roughly two thirds of the energy produced is used to pressurize the air. The idea is to use low-cost power from an off-peak base load facility in place of the more expensive gas turbine-produced power to compress the air for combustion. CAES plants are gas turbine plants with a compressor and a separate turbine, as shown in Fig. 4.

Each turbine is linked to a motor/generator through a clutch. With a CAES system, the energy received from the renewable energy plant is used to run the compressor. The compression is done outside periods of peak demand. As a part of the compression process, the air is cooled prior to injection to make the best possible use of the storage space available. The air is then pressurized to about 75 bars [49]. The compressed air is then stored in a tank that, if available, could be a huge underground cavern. When energy is needed, air is extracted from the reservoir. It is first preheated in the recuperator. The recuperator reuses the energy extracted by the compressor coolers. The heated air is then mixed with small quantities of oil or gas, which is burnt in the combustor. The hot gas from the combustor is expanded in the turbine to generated electricity [50], [51]. The shaft of the turbine then turns a generator and the energy produced is transferred to the utility grid.

Since CAES facilities have no need for air compressors tied to the turbines, they can produce two to three times as much power as conventional gas turbines for the same amount of fuel [52]. Today, there are only two CAES plants in operation in the world, i.e. (i) a 290 MW plant in Germany and (ii) a 110 MW plant in the US. Hence it is seen that in locations where it is viable, CAES can provide an excellent large-scale energy

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option for storing energy in large quantities for large durations. In CAES, gas is released and spins a turbine in order to produce electricity.

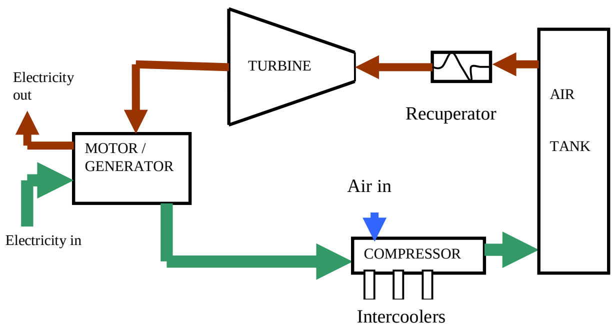


***Fig. 4. Compressed air energy storage block diagram.***

*Advantages*: CAES can be used on very large scales, i.e. facilities can be sized in the range of 50-300 MW. Apart from PHS, no other storage method has a storage capacity as high as CAES. The storage period is the longest (more than a year) as the losses are very small. CAES has fast start up, i.e. it has the ability to start up in around 12 minutes under normal conditions (compared to conventional combustion plants of 20-30 minutes). Also if natural geological formation is used, the installation cost is relatively small. Moreover, a CAES project used in conjunction with a gas turbine requires 66% less natural gas to create the same amount of power.

*Disadvantages*: The main drawback is the reliance upon geological structures.

Compressed air tanks are widely used in industry to provide a constant source of compressed air with uniform pressure in the range of 8-10 bar. There is renewed interest in the compressed air storage for covering the demand of peak electricity or for small wind/hybrid applications, where the energy-to-power ratio of batteries is unsuitable, either because the energy content is very high but the power requirement is low, or the energy through-put is very high as compared to the energy content. Research into whether and how wind energy can be better integrated in the European and German electricity supply by means of CAES power plants is being conducted in various studies, sponsored by the German Federal Ministry for the Environment [53]. Furthermore, research and developments are also being done in solid heat storage tanks that are resistant to pressure.

There are currently CAES power plants in the design phase all around the world; 10 plants are being planned in the USA alone. About 20 companies and institutes are working on Advanced Adiabatic CAES technology. It is expected that there will be systems ready for industrial implementation by around 2015 [53]. In [54] authors have explored the opportunities for energy storage (such as pumped hydro accumulation storage (PAC), underground PAC and CAES) for the integration of large-scale wind power into a future lay-out of the Dutch generation system, for which minimum-load problems are foreseen with high wind power penetrations.

### *D. Battery Energy Storage (BES)*

Storage batteries are an essential part of any self-sufficient renewable energy system that is not connected to a utility grid. Battery banks act as a back-up energy source when the wind speed is less than cut-in wind speed of the wind turbine or when the sun is not shining. Tsai et al. [55] proposed a multi-function BES which is capable of (1) separately controlling the active and reactive power of the BES in the power conditioning mode where the response is fast, (2) charging and discharging battery easily under the constant current or constant power applications, (3) regulating the line voltage in the voltage stabilizer mode by directly controlling the reactive power of the power converter, and (4) compensating the harmonics and reactive power of the load so the harmonics of the utility is reduced in the active filter mode. An integrated wind-battery storage system is shown in In [56], authors showed that integration of STATCOM into BES system exhibits increased flexibility over the traditional STATCOM with improved damping capabilities due to the additional degree of control freedom provided by the active power capabilities.

A BES system requires a charging regulator, which controls the flow of power from the source of electricity to the battery. Proper charging insures minimum battery damage and maximum life of the battery. Battery management system is usually done to achieve maximum system performance, while minimizing power consumption to extend battery life [57]-[59]. Batteries are a long-established means of storing electricity in the form of electrochemical energy.

To choose a particular battery some factors to be considered are

- Battery voltage: this depends upon the system components (inverter) and storage requirements. Most commonly 12 or 24 V DC are chosen.
- Charging and discharging currents
- Maximum charging voltage
- Age of battery
- Temperature, since it affects the performance of batteries and life cycle

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- The ampere-hour efficiency which is the ratio of ampere-hour out to ampere hour in
- Energy density
- Cost of battery
- Maximum number of days of use
- Depth of discharge (DOD) which is the amount of charge the battery discharge of the total charge. Shallow cycle battery has 20 % DOD and deep cycle battery has 50-80 % DOD.
- Energy cost ($/kWh)

There are various types of batteries including

1. Lead-acid Batteries: A lead-acid battery is an electrical storage device that uses a reversible chemical reaction to store energy. The lead-acid batteries have been used in electrical power systems for more than a century.

*Advantages*: It has relatively high efficiency, i.e. it can respond to changes in power demand within seconds. It has low cost and it can operate in temperature in the range of 0-100˚F. It has low stand-by losses.

*Disadvantages*: It has relatively long discharge times. It has low energy density, 30-50 Wh/kg [61]. Batteries are designed to be operated at ambient temperatures. If operated at temperature higher than the designed, then capacity will increase but life-cycle will shorten. If operated at temperature below designed operating temperature then it may last longer but its capacity will decrease.

To avoid valve regulated lead acid batteries going into a thermal runaway, [62] describes a new efficient method of charging batteries employing an intermittent charging technique called “Interrupted charge control”.

2. Sodium-Sulphur batteries (NaS): NaS battery technology involves high operating temperatures, i.e. 300°C. The cell construction uses liquid sulphur as the negative electrode and liquid sodium as the positive electrode, separated by a solid electrolyte of beta-alumina. The battery delivers 100% coulombic efficiency, meaning that all the electricity put into it can be recovered [61]. However, its operating temperature must be maintained. The energy density of NaS battery is 100 Wh/kg.

The sodium-sulphur battery is commercially available and versions of this technology are already being used in Japan and US. However, in U.S. there is an application of the battery as a direct wind energy storage device in MN wind farm [63].

3. Vanadium Redox Battery (VRB): VRB's are based on the patented vanadium-based redox regenerative fuel cell that converts chemical energy into electrical energy. Redox is the term used to describe electrochemical reactions in which energy is stored in two solutions with electrochemical potentials sufficiently separated from each other to provide an electromotive force to drive the oxidation-reduction reactions [64]. In the VRB energy is stored chemically in different ionic forms of vanadium in a dilute sulfuric acid electrolyte. This creates a current that is collected by electrodes and made available to an external circuit. The reaction is reversible allowing the battery to be charged, discharged and recharged.

Currently, installed vanadium batteries include a 275 kW output balancer in use on a wind power project in the Tomari Wind Hills of Hokkaido and a 12 MWh flow battery is also to be installed at the Sorne Hill wind farm, Donegal, Ireland [65]. In Utah, a 250 kW/8-h VRB has been put into service for a long distribution line [66].

*Advantages*: It can offer almost unlimited capacity simply by using larger and larger storage tanks. It can be left completely discharged for long periods with no ill effects. It can be recharged simply by replacing the electrolyte if no power source is available to charge it, and if the electrolytes are accidentally mixed the battery suffers no permanent damage. It has a fast response, has high rate of overload capacity, long cycle life time in deep charge or discharge, has normal temperature operation and has a large open circuit voltage [67]-[68]. Unlike conventional batteries, power output is independent from energy storage capacity and output depends on the size of the fuel cell stack, while the energy storage capacity depends on the size of the electrolyte tanks. Neither constrains the other, although the ratio of storage to power determines how long the batteries can run without recharging. Power can flow undiminished as long as there is fresh electrolyte to circulate through the stack [69].

*Disadvantages*: VRB are a relatively poor energy-to-volume ratio (energy density is 25-35 Wh/kg), and the system complexity in comparison with standard storage batteries.

4. Lithium ion Battery: Lithium ion battery technology has progressed from developmental and special-purpose status to a global mass-market product in less than 20 years. In [70] lithium ion battery is considered as a grey system. The grey prediction technique was then used to develop a grey-predicted Li-ion battery charge system (GP-LBCS) to assess the charge performance. The charge speed and efficiency in the proposed GP mode

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were improved above 34% and 7%, respectively, compared with that in the general CV mode.

*Advantages*: They are generally much lighter than other types of rechargeable batteries of the same size. The electrodes of a lithium-ion battery are made of light weight lithium and carbon. Lithium-ion batteries have a very high energy density (110-160 Wh/kg). They hold their charge. A lithium-ion battery pack loses only about 5 % of its charge per month and they have no memory effect, which means that one does not have to completely discharge them before recharging. Furthermore, lithium-ion batteries can handle hundreds of charge/discharge cycles.

*Disadvantages*: They are extremely sensitive to high temperatures. Heat causes lithium-ion battery packs to degrade much faster than they normally would. Also if a lithium-ion battery is completely discharged, it is ruined. A lithium-ion battery pack must have an on-board computer to manage the battery. This makes them even more expensive than they already are. Furthermore, there is a small chance that if a lithium-ion battery pack fails, it will burst into flames.

In order to maximize the performance of lithium-ion batteries, authors [71] have presented an Ant-Colony-System (ACS)-based algorithm. Experimental results showed that the obtained rapid charging pattern is capable of charging the lithium-ion batteries to 70% capacity in 30 minutes. The obtained pattern also provides 25% more cycle life than the conventional constant current-constant voltage method.

*E. Hydrogen Fuel Storage*

This energy storage system is comprised of two main sub-systems, an electrolysis device and a fuel cell array as shown in Fig. 5. Electrolysis is a process by which electrical energy is used to obtain hydrogen and oxygen from water. The oxygen could be sold or discarded due to the fact that it is highly flammable. On the other hand, the hydrogen would be stored for later use with the fuel cell array. A fuel cell is an electrochemical energy conversion device that does the exact opposite of the electrolysis process; it converts the chemicals hydrogen and oxygen into water and in the process produces electricity.

With a fuel cell, chemicals constantly flow into the cell so it never goes dead, as long as there is a flow of chemicals into the cell, the electricity flows out of the cell. Most fuel cells today use hydrogen and oxygen as the chemicals. If the fuel cell is powered with pure hydrogen, it has the potential to be up to 80-% efficient. That is, it converts 80 % of the energy content of the hydrogen into electrical energy. Fuel cells are costly and the major cost contributors are the membrane, the electro catalyst (due to the platinum content) and the bipolar plates [72].

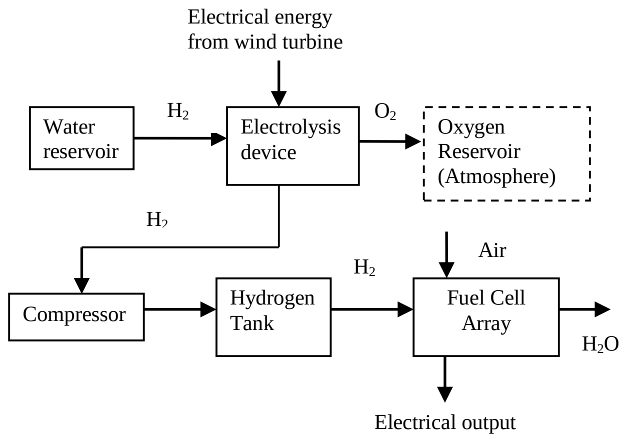


***Fig. 5. Electrolysis/fuel cell block diagram***.

There are many kinds of fuel cells.

1. Solid oxide (SO) fuel cell: These fuel cells are best suited for large scale stationary power generators that could provide electricity for factories or towns. This type of fuel cell operates at very high temperatures (700-1000°C). This high temperature makes reliability a problem, because parts of the fuel cell can break down after cycling on and off repeatedly. However, SO fuel cells are very stable when in continuous use. The high temperature has an advantage, i.e. the steam produced by fuel cell can be channeled into turbines to generate more electricity which improves the overall efficiency. Gebregergis et al. [73] developed a computationally efficient lumped-parameter model for real-time emulation and control of a solid oxide fuel cell. The performance of this model was compared with a detailed distributed model and experimental results.

2. Alkaline fuel cell: This is one of the oldest designs for fuel cells. The alkaline fuel cell is very susceptible to contamination, so it requires pure hydrogen and oxygen. It is also very expensive.

3. Molten-carbon fuel cell (MC): Like the solid oxide fuel cell, these fuel cells are also best suited for large stationary power generators. They operate at 600°C, so they can generate steam that can be used to generate more power. They have a lower operating temperature than solid oxide fuel cells, which means they don't need such exotic materials. This makes the design a little less expensive.

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4. Direct-methanol fuel cell (DM): Methanol fuel cells are comparable to a PEM fuel cell in regards to operating temperature, but are not as efficient. Also, the DM fuel cell requires a relatively large amount of platinum to act as a catalyst, which makes these fuel cells expensive.

*Advantages*: The electrolysis/fuel cell system would have a long life span due to the fact that it does not have many moving parts. It would also be environmentally safe as it only produces water, electricity, hydrogen, and oxygen. Also hydrogen storage has a fast response and switch over, it has low long term losses, and can be scaled to any size [74].
*Disadvantages*: Hydrogen and oxygen (in their pure form) are highly flammable when mixed with air at concentrations of 4-75%. The ignition energy for this mixture is also very small and easily generated from a spark of static electricity (Hindenburg Disaster). The electrochemical materials involved are expensive and it has low overall efficiency.

Currently, there are a lot of research and development being carried out in efficiency of fuel cells and the storage of hydrogen fuel. There are research being carried out by NREL in U.S. to determine if hydrogen could economically produced via wind power for transportation fuel usage [75]. There is an experimental wind to hydrogen system set up running through the collaboration of NREL and Xcel Energy from January 2007 [76]. There has also been a major discovery at Massachusets Institute of Technology on how to efficiently breakdown hydrogen and oxygen from water using electricity from renewable source [77]. A new development from InnovaTek offers potential freedom from high oil prices and hope for the future of biodiesel fuel-cells. They are currently testing a hand-sized micro reactor that can convert nearly any liquid fuel into hydrogen [78]. Research activities are being carried out to develop hydrocarbon membranes which should be less expensive to manufacture than the state-of-the-art per fluorinated membranes [79].

At present a stand-alone renewable energy (RE) system (wind and solar) based on hydrogen storage has been developed at the hydrogen research institute and it was successfully tested for automatic operation with an in-house designed control system and power conditioning devices [80].

## Comparison of the storage technologies

So far it has been separately discussed the different types of storage technologies. Table 1 shows the comparisons

***Table 1***
***Comparison between different storage technologies***

| Energy storage device | Flywheel energy storage | Pumped-hydro storage | CAES | BES | $H_2$ fuel storage |
|---|---|---|---|---|---|
| Capacity (MW) | 0.1-10 | 100-1000 | 0.1-1000 | 0.1-10 | 0.1-1 |
| Duration of storage | Short term (< 15 sec) | Long term (6 months) | long term (> 1 year) | Short term | long term |
| Type of storage | kinetic energy | Potential energy | Potential energy | electro- chemical energy | Electro chemical energy |
| Lifetime | 40 years | 30+ yrs [81] | 30 yrs | 2-10 yrs | 40000 hrs |
| Response time | Very short in ms (5ms) | 10-30 ms | 3-15 min | 30 ms | 0.5 s |
| Duration of discharge at maximum power level | minutes to 1 hour | 12 hrs | 4-24 hrs | 1-8 hrs | Hours as needed [82]. |
| Round up efficiency (%) | 90 | 80 | 60-75 | 60-80 | 50 |
| Energy density | 10-100 Wh/kg | ~2000 Wh/m$^3$ | ~3 Wh/mol | 20-40 Wh/kg (lead-acid) | 20-45 kWh/kg |
| Cost | 150-250 €/kW | 2500-3000 $/kW | $517/kW [82] | 50-250 €/kW (lead acid) | $4.03/kg |
| Operating temperature | normal atmospheric | Normal atmospheric | Normal atmospheric | high 0-100°F for lead acid | 50-120°C |

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## Conclusions

Storage technologies can help make renewable energy, whose power output cannot be controlled by grid operators, smooth and dispatch able. Wind turbines do not need to deactivate in the event of a grid overload, and if there is excess electrical energy, the storage technology refines base-load electricity, converting it to peak-load electricity. Thus, the fluctuating electricity prices on the liberated electricity market can be used to yield profits.

For very large amounts of electricity storage, the availability of geologic formations for compressed air energy storage (CAES) and raw materials for batteries, as well as the need for recycling them, could become limiting factors. If the cost of high strength materials, underground installation, and/or safe containment of accidents limits the maximum deployment of flywheels as well, then electrolysis to produce hydrogen for routine storage for vast amounts of energy worldwide becomes attractive. It is therefore important that hydrogen research and development efforts focus on technologies enabling efficient integration of future carbon-free transportation and electricity generation. Different storage technologies are applied in a power utility. Each storage technology has its own pros and cons and by looking at the specific requirement of energy for a site an appropriate storage technology is chosen. The choice would depend on the location of power utility, the costs involved, the efficiency and energy density of the storage technology. Analytical studies have shown the applicability of energy storage for voltage support and frequency stability, for peak shaving, renewable firming, transmission upgrade deferral and a host of other uses.

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