

Current Trends on Energy Storage Technologies

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Energy storage technologies are becoming ever more important in power systems because of the increasing implementation of renewable energy sources as well as their technical, economic and environmental benefits. It is important to understand how these technologies operate, their characteristics, their effect on the traditional grid system and how they can be effectively utilized for industrial, domestic and commercial customers. This paper aims to provide an overview of the existing energy storage technologies and demonstrate how they are being employed efficiently in power systems. A comparison of various energy storage devices, system requirements and classification of energy storage technologies in terms of response rate, life cycle, operational cost and their energy capabilities will be addressed.

Introduction

Fossil fuel has been the major source of electricity in the world. However, in recent years, the increasing implementation of renewable energy sources such as wind turbines, photovoltaic solar systems, fuel cells, biogas and hydropower turbines means that there will be a reduced dependence on fossil fuels in the future. Renewable energy sources are being exploited because of the accelerated depletion of energy resources from fossil background [1], climate change concerns and greenhouse emission, and increasing demand of electricity. However, the varying and intermittent nature of renewable energy sources makes them difficult and unpredictable to control when connected to the grid. Energy storage can be used to compensate for the deficiencies of renewable energy sources. With energy storage technology, some of the control lost using renewables can be recovered, allowing generation and demand requirements along with grid performance to be aligned and controlled more closely [2].

This paper aims to offer an overview of the current state and future trends of energy storage technologies. The benefits of energy storage will be provided. Various energy storage technologies will be classified and a detailed technical comparison between the technologies will be made. A

comprehensive discussion on the application and effect of energy storage technologies will be provided. Finally, future advances and development of energy storage will be examined

Importance of Energy Storage Technologies

When utilized properly, energy storage technologies can provide environmental, economic and technical benefits to energy supply systems. Some of the benefits are as follows:

A. Back-up for Power Supply

The obvious benefits of storing energy is its ability to serve as a back-up to power supply. During sudden load changes and short-term fluctuations, stored energy can be used to provide power to the grid. In addition, energy storage technologies can serve as a long-term back-up power in the event of a large power outage or failure [3].

B. Supply and Demand Matching

Electrical energy can be stored during times when power supply is greater than load demand, mostly at a lower cost. The stored energy can be released to the power grid when the demand of energy exceeds the supply, probably at a higher cost. This enables traditional power generation plants to operate more efficiently and easily at constant production levels. Storing energy at low cost and supplying the stored

energy at a higher cost provides profit and cost benefits.

C. Power Quality

Energy storage technologies, when properly implemented can provide electrical energy to customers (especially industrial customers) without any secondary fluctuations or momentary interruption. This overcome power quality challenges such as swells/ sags, spikes, or harmonics.

D. Enabling of Renewable Energy Sources

This is the most important benefit of energy storage technologies. Renewable energy sources such as the sun and wind are increasingly being exploited to generate clean energy. Their power supply however, is intermittent and erratic [2]. Energy storage technologies can be used to smoothing the varying and intermittent nature of the power input associated with renewable energy sources. Surplus energy produced at the time of supply (for example, during the day when the sun is out) can be stored for use during periods of high demand.

E. Reduction of Greenhouse Emission

Greenhouse gas emission from the energy industries will increase about 55% between 2004 and 2030 with oil and coal as the main contributor of global carbon dioxide emission. Energy storage technologies enables optimization of power supply, stabilization of transmission and grid distribution which will achieve a reduction in greenhouse gas emission.

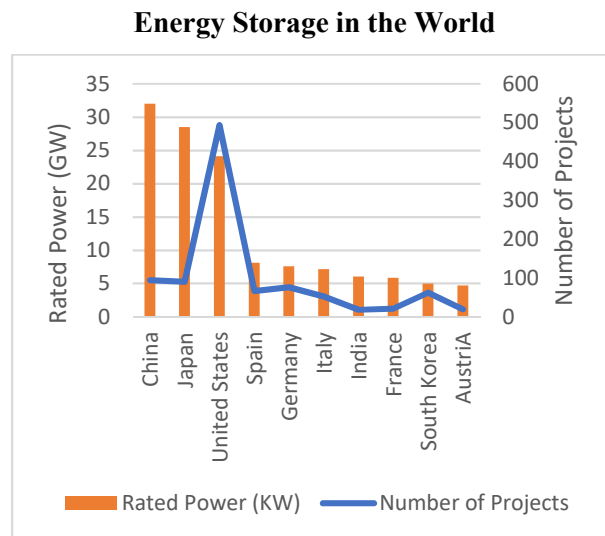


Fig.1: Energy storage capacity and projects in top 10 countries [4]

In the world, China has the largest installed capacity of energy storage technologies with about 32GW rated power. The United States has the third largest installed capacity of energy storage with a rated power of 24GW. There are currently as many as 494 projects on energy storage technology being carried out in the United States. This is the highest for any country. European countries such as Spain, Germany and Italy are with large installed capacities of energy storage technology. In Africa, South Africa has the highest installed capacity of energy storage with rated power of 3.25GW [4].

Energy storage technologies are becoming ever more important in the world today. As reported by the Department of Energy database [4], there are currently a total of 1,267 Energy storage projects being carried out all over the world.

Composition of Energy Storage Technologies

Energy storage technologies are made up of four major components [5];

- Storage Medium: the means or system which will store the energy until it is needed.
- Charging System: the unit that allows energy flow from an external network into the storage medium
- Discharging System: the unit that delivers the stored energy when required
- Control System: the unit that governs the whole operation of the energy storage system

Classification of Energy Storage Technologies

Energy storage systems can be either classified by their response characteristics or by the form in which the energy is stored. Based on their response characteristics, energy storage systems can be classified into three categories [3];

- Short Term Response Energy Storage Technology: absorbs and supplies electrical power in a short time frame (seconds or minutes). Usually applied to improve power quality and maintain voltage stability during transients.
- Long-Term Response Energy Storage Technology: responds for minutes or hours. They are applied for frequency regulation and energy measurement.
- Real Long Term Response Energy Storage Technology: responds for days, weeks or months.

They are usually used for supply and demand matching, energy management and reserve capacity.

Based on the form in which the energy is stored, energy storage technologies can be classified into; electrical energy storage system, mechanical energy storage system, thermal energy storage system and chemical storage system.

Energy Storage Technologies

Many energy storage technologies have been developed for various applications. New technologies are also being designed. This section gives an overview of existing and developing energy storage technologies.

A. Pumped Hydro Energy Storage (PHES)

Pumped hydro energy storage has the largest energy storage capacity in the world. It is also the most widely used large scale energy storage system representing more than 99% of worldwide storage capacity [6]. This system normally comprises of a turbine/generator, a pump, an upper level reservoir and a lower level reservoir. During off peak (low cost) electricity hours, water is pumped to the upper level reservoir. At periods of high electricity demand, the stored water is released through the turbine/generator. The amount of energy that can be stored in a PHES system depends on both the size of the upper level reservoir and the height between the upper and lower level reservoirs [7]. The rated power of PHES system depends on the water pressure and the flow rate of the pump and turbine/generator unit [6]. The pumped hydro storage is classified as a real long term response energy storage technology. It has a typical rating of approximately 1000MW [8]. However, PHES is limited by land topography because it requires two large areas of land (for reservoirs) which must be located at different heights [5].

B. Compressed Air Energy Storage (CAES)

Compressed air energy storage system is considered as one of the cheapest energy storage technology in terms of capital cost (\$/kWh) and maintenance cost (\$/kW-year) [9]. CAES store energy in the form of compressed air. The CAES pre-compresses air using off peak electrical power from the gridline and stores it in large underground

caverns at a very high pressure [3]. The pressurized air is then released and mixed with fuel before being heated to drive an expansion turbine to generate electric power. CAES is also classified as a real long term response energy storage technology and is most commonly applied to provide backup power during long blackouts. Currently there are two large scale CAES plants in operation, one in Huntorf, Germany with a capacity of 290MW, and the other in Alabama, USA with a 110MW capacity [10]. Compared to other Energy storage technologies, the CAES has a relatively low cycle efficiency [9].

C. Adiabatic Compressed Air Energy Storage (ACAES)

The adiabatic compressed air energy storage system is a proposed technology similar to the CAES system. Just like the CAES system air is compressed and stored in an underground cavern, but unlike the CAES, heat is extracted from the stage of compression and stored in an adiabatic reservoir. The heat is then reused for the air expansion in turning the turbine to generate electric power. The system is designed to eliminate the need for fuel in CAES technology. The ACAES is proposed to have an improved efficiency than the CAES system [9].

D. Flywheel Energy Storage (FES)

Flywheel energy storage technology stores energy in the form of kinetic energy. FES system is composed of five primary components; a flywheel, a group of bearings, a reversible electrical motor/generator, a power electronic unit and a vacuum chamber. The system is charged by operating the generator as a motor and using it to increase the rotational speed of the flywheel. The flywheel is then discharged when the electric machine regenerates through the drive (reducing the flywheel speed) [11]. FES can be classified into either high or low speed. High speed FES provides a long period of time of storage but low power capacities while low speed FES provides a short period of storage but high power capacity [10].

E. Superconducting Magnetic Energy Storage (SMES)

The superconducting magnetic energy storage system stores electrical energy in the form of a magnetic field generated by the direct current (DC) passing through a cryogenically cooled super-

conducting coil. A typical SMES system is composed of three primary components; a superconducting magnetic coil, a power conditioning system, and a cryogenic refrigeration unit [2]. The most commonly used superconducting material is Niobium-Titanium which has a superconducting temperature of 9.2K. The amount of energy is determined by the self-inductance of coil and the current flowing through it [6]. SMES is classified as a short-term energy storage technology. Its power capacity ranges from 0.3 -3.0 MW and is suitable when the application needs a fast response time such as power quality problems and transient stability improvements [12]. SMES are efficient and reliable however they are very expensive, sensitive to temperature.

F. Capacitor Energy Storage (CES)

Capacitors energy storage stores energy in the form of electric charges distributed on two metallic plates separated by thin layers of a dielectric material [13]. The amount of energy which can be stored depends on the size of plates, plate separation and the material used for the dielectric [11]. CES can withstand thousands of charge/ discharge cycles without material degradation occurring [5]. Capacitors are appropriate for storing small quantities of electrical energy because they have a high-power density and shorter charging time. However, they have a limited capacity, relatively low energy density and high energy dissipation due to the high self-discharge losses [6]. CES is classified as a short-term response energy storage technology.

G. Supercapacitor Energy Storage (SES)

Supercapacitors are also known as ultracapacitors or Electric Double Layer Capacitor (EDLC). If the electrode surface area of the conventional capacitor is increased by a special technique, then the capacitor becomes a supercapacitor/ ultracapacitor/ ELDC [13]. With a larger surface area, relatively large amounts of energy can be stored. ELDC have very high capacitance usually in the range of kilofarads compared to the conventional milli or microfarads capacitors. Just like the CES system, the superconductor energy storage system can withstand a high number of charge/ discharge cycles without degradation. SES is also classified as a short-term response energy storage technology [2].

H. Battery Energy Storage (BES)

Battery energy storage system is one of the oldest technologies for energy storage. It stores energy in the form of chemical energy. Batteries consists of two or more electrochemical cells. These cells convert electrical energy to chemical energy when charging and converts chemical energy to electrical energy when discharging [14]. BES system has a wide range of power storage capability (100W - 20MW). This makes it suitable for different application [3]. Few of the widely-used BES technologies referred to as batteries includes:

- Lead acid batteries
- Lithium-ion batteries
- Nickel batteries
- Sodium sulphur batteries
- Metal-air batteries

Lead acid is one of oldest and mature battery storage technology. It is still a widely-used BES technology because of its low cost, negligible maintenance requirements and low self-discharge rates. However, its use has been hindered due to its high toxicity, increased weight due to lead content, and low power density. Lead acid battery energy storage is popular for applications such as Uninterruptable Power Supplies (UPS). Lithium-Ion Batteries on the other hand are lightweight and have achieved a significant penetration in the field of consumer electronics. They have very high energy densities and high efficiencies and can be used as power source within medical devices [2]. Nickel batteries are commonly found in two forms, depending on the application; in its sealed form in portable equipment, and in its flooded form in general industrial application. Nickel batteries have long cycle life (more than 3500 cycles), and low maintenance requirements. However, it is very toxic and suffer from the memory effect [11]. Sodium-Sulphur batteries is another type of BES technology that has high energy density, high efficiency and deep discharge tolerance. This technology is currently employed in large scale energy storage applications such as renewable energy management and integration [2]. Metal-air battery is the most compact and potentially cheapest battery energy storage technology in the market. The application of metal-air batteries is limited to small scale energy storage. It has a low efficiency of around 50% due to its inefficient electrical recharging [10].

I. Flow Battery Energy Storage (FBES)

Flow battery energy storage is a relatively young energy storage technology. Just like the conventional batteries, FBES stores energy by converting electrical energy to chemical energy. Unlike conventional batteries FBES uses two aqueous electrolytic solutions contained in separate tanks. During the normal operation of the battery, these aqueous solutions are pumped through an electrochemical cell, where a reversible electrochemical redox reaction occurs and electricity is generated [10, 11]. The major commercially available FBES includes;

- Vanadium Redox Battery (VBR)
- Zinc Bromine Battery (ZBB)
- Polysulphide Bromide Battery (PSB)

One major advantage of FBES technology is that their energy capacity is easily scalable, since it depends on the volume of the stored electrolyte. FBES technology have both a long lifespan and low maintenance requirement making it suitable for long term energy storage [11].

	Storage Capacity (MWh)	Power (MW)	Discharge Time	Effeciency (%)	Energy Density (Wh/kg)	Cost		Lifetime (Years)	Stage of Development
						(\$/kW)	\$/kWh		
PHES	500-8000	100 - 5000	20hr-100hr	75-85	0.3-1.5*	>1000	15-150	>40	Available
CAES	~1000	3-400	5hr-50 hr	60	10-30	400-1000	10-100	>40	Available
ACAES	-	3-400	Hours	70	-	-	10-100	>40	Design
FES	0.75-5	0.25	10 sec-40 min	95	5-70	>500	800-2200	20-30	Available
SMES	<0.0015	0.1-10	1sec - 40sec	92-97	1-11	300	>20000	40	Developing
CES	-	0.05	1sec-10sec	90	5-25	400	>10000	5	Available
SES	0.0005	0.3	1sec - 30sec	95	<50	300	>25000	30-40	Developing
PbA	<40	0-40	1hr-6hr	70-80	20-45	>200	<300	2-10	Available
Li Ion	<10	0.1	1hr-3hr	70-95	100-200	>300	>1200		
Ni Battery	6.75	0-40	1hr-6hr	75	40-80	>200	400-600		
NaS	0.4	0.05-8	6hr-12hr	86	120-240	>1000	400-800		
Metal-air	-	-	1hr-5hr	50	200-2000	50-200	<300		
VBR	<60	<3	1hr-15hr	85	25	1280	>500	10	Developing
ZBB	<3	0.1-15	sec-10hr	75	30-60	-	900	10	Developing
PSB	0.06	0.1-15	-	75	20-30	-	-	15	Developing

Table 1: Technical Characteristics of Energy Storage Technologies [1-3, 5, 6, 10, 11, 13, 15, 16]

Characteristics of Energy Storage

It is important to analyze critically the technical and economical characteristics of energy storage technologies in order to establish a comparison criteria for selecting the best technology for a specific application. The main characteristics of various energy storage systems are shown and compared on Table 1.

Application of Energy Storage Technologies

Energy storage technologies when applied properly can provide great benefits to the electrical power system. This section presents the typical applications of the energy storage technologies described above.

A. Energy Arbitrage

Energy arbitrage refers to earning a profit by charging energy storage systems with cheap electricity when the demand is low and selling the stored energy at a higher price when the demand is high [15]. Energy arbitrage can also be used such as using higher peak prices to induce a reduction in peak demand through demand charges, real-time pricing, or other market measures. Typically, the pumped hydro energy storage system has been used for energy arbitrage because it can be constructed at large capacities and discharged over a long period of time. The compressed air energy storage is another technology that can be implemented for

energy arbitrage, again due to its large capacities and relatively long discharge times [2, 15].

B. Grid Black Start

Energy storage technologies can be applied in power generating facilities to restore power during total grid power loss. This process is known as black start. Typically, batteries are used as a source of power to start a diesel generator or similar devices, which can then be used to generate electrical power back to the grid.

C. Integration of Renewable Energy Sources

Renewable energy sources of energy such as wind, solar, have gained increasing importance in power system. However, despite of their technical and environmental benefits, the intermittent nature of wind and solar energy systems causes voltage and frequency fluctuations on the electric grid. Integrating renewable energy sources to the grid introduces new issues on the operation of the power system, such as potential unbalancing between generation and demand [17]. It is necessary to employ energy storage technologies with high cycling lifetimes and short response times. Supercapacitors, batteries and Superconducting magnetic energy storage are therefore suitable for this purpose [11].

D. Load Shifting and Load Levelling

Due to the stochastic nature of renewable energy sources, output does not always coincide with the times of peak energy demand of the grid. Load shifting allows delivery of renewable energy to be delayed from periods of non-peak demand to periods of peak demand. Energy storage technologies can store the renewable energy output during low demand periods and release it into the grid when demand is high. This helps to smooth excess demand on the grid and maximize the value of renewable energy. Energy storage technologies such as the adiabatic compressed air energy storage, pumped hydro energy storage, a combination of compressed air energy storage and flywheel can be used for this application [16]. Load levelling similar to load shifting refers to the use of electricity stored during times of low demand to supply during peak electricity demand. This reduces the need to draw on electricity from peaking power plants or increase the grid infrastructure [15].

E. Transmission and Distribution Upgrade Deferral

Transmission and distribution (T&D) upgrade deferral refers to delaying or avoiding investments in upgrading transmission and distribution infrastructure. This is achieved in a power system by the installation of either a temporary or permanent electrical energy storage downstream of the overloaded T&D node [14]. T&D key benefit is that annual carrying charges for capital investment can be avoided, thereby reducing the overall cost to ratepayers, improving asset utilization and reducing the risk associated with lump investments [14].

F. Voltage/ VAR Support

Voltage/ VAR support is an ancillary service usually provided by power system operators to assist in maintaining grid system stability. It requires the absorption of reactive power in order to maintain grid voltage within a specified range [14]. Since reactive power cannot be effectively transmitted over long distances, energy storage technologies offer a viable alternative to provide voltage/VAR support.

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