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A Review of Energy Storage Systems for Wind Power Plants

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Abstract— **The worldwide consumed energy is increasing every year by technological developments and incremental of the population. The growing energy demand is generally covered by exhaustible resources. However, using fossil fuels damage environment. For this reason, Wind Power Systems, type of renewable energy, are preferred for establishing new power plants. Wind Power Plants (WPP) are installed every year with a significant increasing rate. Integration of large scale WPPs into grid presents some issues, such as power quality, bridging power and energy management. State of the art the Energy Storage (ES) is a possible solution for Wind Power Plants.**
In this paper, possible ES technologies for decreasing disadvantages of WPPs are discussed and their characteristic features are compared. ES systems are indicated in terms of purpose of use in WPPs.

Keywords— **Energy Storage, Wind Power Plants, Renewable Energy**

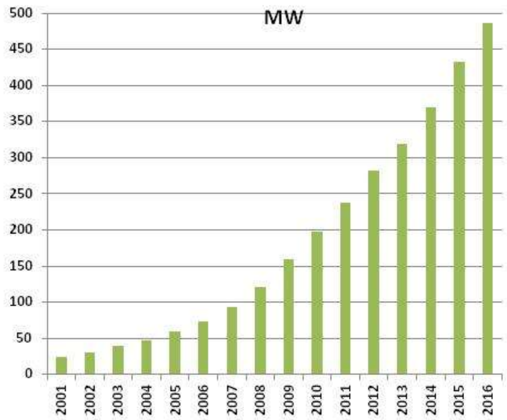
I. INTRODUCTION

Today's need for energy is increasing in parallel with the continuous production of industrial and individual energy consumption. Fossil fuels have a large share of the electricity generation all over the world (81,203% -2013) [1]. However, the harmful gases occurred by using the fossil fuels cause global warming and climate change. In 2005 Kyoto Protocol (United Nations Framework Convention on Climate Change) was entered into force in order to minimize the negative effects on environment [2]. Some countries even decommissioned their old nuclear facilities and decided not to build a new nuclear facility in consequence of environmental concerns (Maine Yankee Nuclear Plant – Wiscasset, ME, USA) [3, 4].

Renewable energy sources became crucial due to decreasing the level of fossil fuels, environmental issues and increased fuel prices. Renewable energy sources, such as wind and solar energy, contribute to electricity generation to become [illegible]

[illegible] MW at height of 1000 m. Principally, this power rating can meet 20 times more the total global energy consumption [5]. In the last decade, the investments focused on wind energy provide a significant speed to establish new WPPs (Table 1). However, instantaneous varying wind speed and its intermittency can present issues. Increasing capacity of WPPs brings imbalance on the system. Fluctuations of voltage and frequency, which are occurred by wind power, make the integration of WPPs to the grid difficult [4, 6]. Energy storage systems have an important role in order to mitigate the negative effects of wind power systems. Beside this, ES systems are used for storing excessive energy in order to use when the energy demand is high.

TABLE I. GLOBAL CUMULATIVE INSTALLED WPP CAPACITY [11]



ES systems are theoretically based on the principle of converting electrical energy into the different dimensions. These systems are; Mechanical Systems (Pumped Hydro Energy Storage, Compressed Air Energy Storage, Flywheels), Electrochemical Systems (Batteries), Chemical Systems (Hydrogen Energy Storage).

II. PUMPED HYDRO ENERGY STORAGE

Pumped hydro energy storage (PHES) systems, which consists of two sections, the upper and the lower reservoir, is one of the largest and the most mature energy storage technology in the world. During off-peak time, surplus energy capacity is used to pump water from lower reservoir into upper reservoir. During times of high demand of electricity water flows, through a hydroelectric turbine, to lower reservoir to generate electricity [8]. The use of reversible turbine-generator structure with improved technology has raised the efficiency of PHES.

$$E_{stored} \propto V(H_{upper} - H_{lower})$$

$$P = \rho g Q H n \quad (2)$$

In the equations (1) and (2) the symbols indicate; V: volume of water (m^3), H: height of reservoir (m), ρ: water [illegible] gravity (m/s^2), Q: flow rate through the turbines (m^3/s), n: efficiency. When the vertical distance between two reservoirs indicated by ''H'' increases the system can be stored more energy.

Worldwide, there are approximately 350 installations with a total capacity of 150 GW [9]. In the last decade especially China has enhanced their investment in PHES. China has built 24 PHES stations with an installed capacity of 22.5 GW at the end of 2014, while government's target of 2020 is 50 GW [10, 12]. PHESs technically have a power capacity of 30-4000MW, an energy capacity of 500-8000 MWh and 70-85% efficiency. With an average lifetime of more than 50 years, PHES have a cycling capacity between 20000 and 50000 [13, 14]. Due to high energy storage capacity and long discharge times, PHES is appropriate for large-scale energy storage. Besides, very low

self-discharge feature makes PHES extremely convenient for long-term energy storage.
When PHES considered as a hybrid system with wind turbines, features such as flexibility of switching, fast response (Table 2), frequency and voltage regulation, load leveling and energy arbitrage provides system an advantage.

TABLE II. THE RESPONSE TIME OF FACILITIES [15]

Type of Facilities	Response Time
Classical Hydropower Facilities	3 - 5 min
PHES	3 - 5 min
Fuel Oil Facilities	3 h
LNG-Natural Gas Facilities	3 h
LNG Combine Facilities	1 h
Coal Fired Facilities	4 h
Nuclear Facilities	5 day

The major drawbacks of PHES, which are high capital cost, long repayment time and suitable site selection, restrict the interest in PHES.
Nowadays studies are also being carried out on Seawater PHES and Underground PHES to enhance the system.

III. COMPRESSED AIR ENERGY STORAGE

Compressed air energy storage (CAES) is a quite old technology, but there are only two stations in the world [13]. The principle of CAES is to store surplus energy in the form of compressed gases. Theoretically in CAES, excess energy drawn from production centers is used on compressors to store air in an underground cavern. The compressed air has high pressure (usually 40 – 80 bar) and high temperature values. In this process, the temperature of sending air is controlled by intercooler and aftercooler to minimize the thermal stress that may occur in the reservoir walls. In addition to that using intercooler and aftercooler increase compressing efficiency.

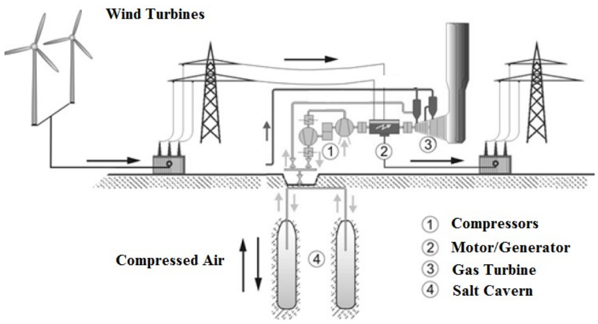


Fig. 1. Schematic Diagram of CAES

When energy demand is high, compressed air is released and sent to high pressure turbine. During this process the air is heated up and expanded. The air, which is enriched with fuel, is sent from high pressure turbine to low pressure combustion chamber and burned. High and low pressure turbines are connected to generator to generate electricity. The waste heat of the exhaust during the combustion process is potentially captured by a recuperator to preheat the compressed air as in McIntosh CAES [21]. The airflow from the reservoir to the turbines must have a sufficient flow rate to supply the need of the system. For instance, the flow rate of the gas in Iowa Energy Storage Park was not at adequate level, which has prevented the project from taking place [18, 20].

In the examples given in Table 3, Huntorf CAES has more power density in comparison with McIntosh CAES. However, McIntosh CAES has a long time energy supply potential with the occasion of their high energy density. Furthermore McIntosh CAES in comparison with Huntorf CAES regains waste heat via recuperator which reduces fuel consumption by 25% [16].

TABLE III. TECHNICAL FEATURES OF HUNTORF CAES AND MCINTOSH CAES [23]

Location	Huntorf Germany	McIntosh USA
Commissioned	1978	1991
Store	Salt Cavern	Salt Cavern
Volume of Store	2 x 150 000 m3	538 000 m3
Depth of Store	650 - 800 m	450 - 750 m
Energy Required for 1 kWh electric	0.8 kWh electricity 1.6 kWh gas	0.69 kWh electricity 1.17 kWh gas
Pressure Tolerance	50 - 70 bar	45 - 76 bar
Output	290 MW for 2 hours	110 MW for 26 hours

A. Adiabatic CAES

The requirement of additional fuel is eliminated by replacing the combustion chamber in conventional CAES with thermal energy storage. Adiabatic CAES is a promising technology under favour of scalability, environmentalism, high energy storage efficiency and less dependence on fossil fuels [23]. However, there are still a number of challenges to overcome: heat storage tanks, compressors and turbines which should be resistant to high temperatures (600^{o}C), yet to reach the adequate technological levels. These are the most significant obstacles against the development of this method [21].

B. Small Scale CAES

Large-scale CAES requires generally suitable geological conditions for storage. However, small scale CAES, with a power capacity of 1-10 MW, having artificial pressure vessels is a more flexible CAES option without caverns and thermal energy storage [24].

C. Isothermal CAES

Conventional CAES and adiabatic CAES have some drawbacks such as; fossil fuel use and 'High Temperature' heat energy storage. This emerging technology offers a relatively low cost and an improved round trip efficiency (RTE) to eliminate the drawbacks of conventional CAES and adiabatic CAES [23].
Compressed air energy storage system technically has a power capacity of 50-300MW, a energy capacity of 500-2500 MWh and 64-75% efficiency. CAES have a cycling capacity between 10000 and 30000 with an average life span of 40 years [13, 14]. Compared to PHES, it has lower energy and power capacity. Nevertheless, CAESs high energy capacity makes it suitable for large scale energy storage.
When CAES considered as a hybrid system with wind turbines, features such as peak shaving, VAR support, energy arbitrage and high cycling capacity that makes possible to cut-in/out, provides system an advantage.

Nowadays, researches carried out that CAES should collaborate with super capacitor in order to measure up energy capacity, energy density, response time and efficiency.

IV. BATTERIES

The energy is stored in the form of electrochemical energy, in a set of multiple cells, connected in series or in parallel or both, in order to obtain the desired voltage and capacity [19]. Each cell, shown in Figure 2, consists of; anode which provides electrons to the load and is oxidized, cathode which accepts electrons and is reduced, electrolyte which provides transfer of electrons between the anode and the cathode and the separators [4].Load following, spinning reserve and elimination of forecast uncertainties are some applications of batteries in wind turbines. Due to their fast response time (~20ms) and high RTE; lead acid, lithium-ion, nickel cadmium and sodium sulphide are used in these applications [33].

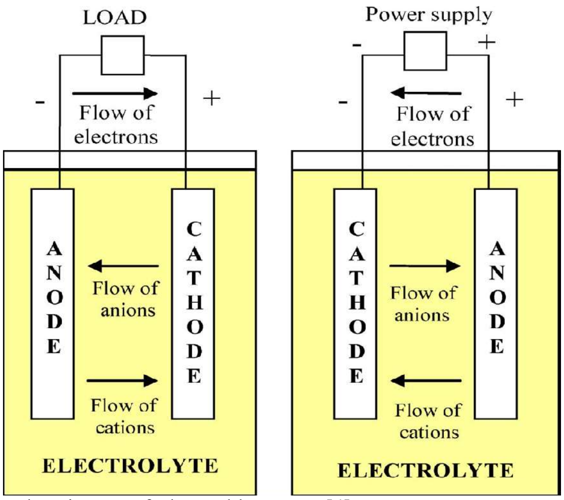


Fig. 2. The Diagram of Chargeable Battery [4]

A. Lead Acid Batteries (LA)

LA batteries are the most mature and the oldest battery type with low capital cost and relatively low maintenance cost. These type of batteries have a power capacity of 0.01-10 MW, a energy capacity up to 40 MWh and each cell voltage is 2 V. The limiting factors of lead acid batteries are low cycling times (1200-2000) and lifetime (5-15 years). Cycling times is negatively affected by depth of discharge and temperature. If lead acid batteries are fully discharged, especially the electrodes are damaged, which can reduce the battery life [4, 13, 14].

Currently, emerging lead acid batteries are investigated to have higher energy density, cycling capacity and depth of discharge. In 2013, advanced lead acid batteries (36 MW/24 MWh) were built for a wind farm, which has 153 MW installed capacity, in West Texas (USA) region [31].

B. Nickel Cadmium Batteries (NiCd)

NiCd batteries are alongside LA batteries one of the most mature battery type. Nickel cadmium batteries, which are used in portable devices, electrical appliances and electrical vehicles, have been largely displaced from markets because of the harmful effects of cadmium component. Despite this disadvantage, nickel cadmium batteries are an alternative to lead acid batteries due to their high power capacity (0.01-40 MW), more cycling times (2000-2500) and low maintenance costs [13,14].

In Golden Valley (Alaska, USA) nickel cadmium batteries with a nominal power of 27 MW for 15 minutes or 40 MW for 7 minutes and 72-78 % efficiency put into use in 2013 for energy storage [29].

C. Sodium Sulphide (NaS)

Sodium sulphide batteries, which have been in use since the early 2000s, have a long cylindrical shape as a cell form. These types of batteries have high efficiency and require high operating temperature to remain sodium element in liquid (300-350^{o}C).

The energy density of these batteries is about three times higher than lead acid batteries (150-240 Wh/kg) [8]. Due to high operating temperatures and high corrosion content, NaSs are more suitable for large scale applications. It can be also integrated with wind turbines to regulate peak loads and increase power quality. For this purpose in 2008 sodium sulphide batteries with a capacity of 34 MW/204 MWh were built for a wind farm, which has 51 MW installed capacity, in Japan (Rokkasho Wind Farm) [31].

Nowadays, researches are underway to reduce operating temperatures in order to increase the performance of sodium sulphide batteries.

D. Lithium-ion Batteries

Since 1990s, lithium-ion batteries widely used in 3C (Communication, Consumer Electronics, Computer) applications. On the other hand lithium-ion batters have commenced to play an active role in electric vehicles and energy storage with new researches and developments.

Li-ion batteries has a low self-discharge rate, thus these batteries are favorable for long term energy storage. Also, they have high power capacities. Due to these specifications, li-ion batteries can be used for seasonal energy storage and energy management. Nevertheless, these batteries are still new and developing so their costs are relatively high.

In comparison with NiCd and LA batteries, lithium-ion batteries have higher energy density (75-200 Wh/kg) and efficiency, lower self-discharge rate (1-5%) and much lower maintenance costs. Compared to other batteries, lithium-ion batteries are more efficient cellular voltage with values of 3.7 V [4].

Depth of discharge and high capital costs are the most significant drawbacks of these batteries. While depth of discharge has an effect on the battery lifetime, the devices on the battery, which controls the battery groups, cause high cost [32].

In recent years, researches and developments are enhanced to increase the specific energies of batteries by using nano scale materials. In Hawaii (USA), lithium nanophosphate batteries with a capacity of 11MW/4300kWh were used in a wind farm, which has 21 MW power capacity, to regulate the fluctuations in production [31].

In table 4, comparative information is given in related with characteristic features of the batteries. When energy densities and capacities of the batteries are taken into consideration, NaS and Li-ion batteries are more favorable for large scale applications. Mostly, batteries have fast response time. That's why they are used in such as emergency and telecommunication reserve applications which are required a fast response time.

TABLE IV. COMPARISON OF TECHNICAL CHARACTERISTICS OF BATTERIES [13, 14, 19, 32]

	Lead-Acid	NiCd	NaS	Li-ion
Energy Density (Wh/l)	50 - 90	60 - 150	150 - 300	200 - 500
Power Density (W/l)	90 - 700	80 - 600	140 - 180	1500 - 10000
Energy Rating (MWh)	0.01 - 40	up to 6.75	0.01 - 1200	0.004 - 10
Power Rating (MW)	0.01 - 20	0.01 - 40	0.01 - 34	0.01 - 100
Lifetime (Years)	5-15	10-20	10-20	5-15
Daily Self-Discharge (%)	0.1 - 0.3	0.2 - 0.6	~0	0.1 - 0.3
Response Time	Milliseconds	Milliseconds	Milliseconds	Milliseconds
Cycling Times	500 - 2000	2000 - 3000	2500 - 4500	1000 - 20000
Discharge Time	Seconds - Hours	Seconds - Hours	Seconds - Hours	Minutes - Hours
Efficiency (%)	70 - 90	60 - 80	75 - 90	90 - 95
Voltage (V)	2	1.2	2.1	3.7
Suitable Storage Duration	Minute-Days (Short-Medium Term)	Minute-Days (Short-Long Term)	Hour-Weeks (Long Term)	Minute-Days (Short-Medium Term)

Nickel Cadmium batteries have a cell voltage rate of 1.2V. NiCd batteries have lower voltage than the other batteries can seen at table 4, so they need more cells to meet same voltage level. NiCd and LA batteries have similar features. Lead acid batteries are in operation at some places such as BEWAG Berlin, Chino California, Kahuku Wind Farm Hawaii. In these applications LA batteries are used for frequency control, load leveling and bridging power. NaS batteries, in Rokkasho Wind Farm Japan, Graciosa Island Germany and Saint Andre France, are preferred for mitigating the fluctuations of wind power, peak shaving and long term energy storage [19].

V. HYDROGEN ENERGY STORAGE (HES)

Hydrogen as a fuel is storable, transportable and environmentally friendly, hence it is expected that they can replace the other fuel options. Besides these features, hydrogen has high energy and power capacity so the researches focused on using it as an energy storage device [13]. The promising HES method has 3 stages: hydrogen production, storage and usage. Hydrogen is produced by extraction from fossil fuels, reacting steam with methane, electrolysis and biomass. However, hydrogen production by fossil fuels or natural gas is not efficient in terms of costs and also they damage environment. Considering these reasons, the interests for electrolysis are increasing. Recently, it has not used widespread due to the fact that generating electricity is expensive. Hence, it is estimated that if electrolysis process is provided by renewable energy, the cost of electrolysis can reduce [8].

Electrolysers are classified in terms of type of electrolyte. There are a lot of electrolyte types but the most common one is Polymer Electrolyte Membrane (PEM). Solid electrolyte using with PEM has hydrogen production capacity rate of up to 10 N m^3/h at 200-6000 psi [19, 22].

Consequently, produced hydrogen during the electrolysis is stored form of solid, liquid and gaseous. Compressed hydrogen is stored in metal tanks (or carbon fiber as composite material, polymer) and it is the most common one. The other method, based on the principle of compressing the gas and cooling, is storing hydrogen in liquid form but cooling process is required rather much energy. In solid state storage is achieved by combining hydrogen with various compounds (metal hydrides, borohydrides, methanol, carbon nanostructures). Solid state storage is more efficient than the other methods because of its leak-proof structure [25].

Stored energy is used when the energy demand is increasing in order to generate electricity by using fuel cells. To convert the energy; Polymer Electrolyte Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC) and Solid Oxide Fuel Cell are used. Due to its low operation and maintenance costs, PEMFC is preferred mostly [19].

Practically, HES's self discharge rate is zero and it leads to the system storing long-term energy. HES systems have more than 20 years' lifetime and cycling rate of 20000. This system is also suitable for large-scale storage applications with WPPs because it has power capacity up to 50 MW and energy capacity up to 120 MWh. The first application of HES systems integrated with WPP put in use in 2004, Utsira, Norway [30]. But the efficiency of the systems (almost 40%) is one of the important obstacles for spreading [19, 32].

The recent studies are focused on new materials and developing the current materials in order to increase the efficiency of electrolyser, storing tanks and fuel cells.

VI. FLYWHEELS ENERGY STORAGE (FES)

Flywheel is a rotating mass that stores energy in kinetic form. The surplus energy in the grid used on flywheels to rotate the mass. The rotational speed is increased proportional to desired storage rate. When the energy demand rises, the flywheel's velocity is reduced and as a following step, the desired amount of the recent kinetic energy is driven to the generator in order to generate electricity. Stored Energy (E) depends on inertia (I) and angular velocity (ω). Energy in flywheels is calculated by equations (11), (12) and (13).

$$E = \frac{1}{2} I\omega^2 \quad (11)$$

$$I = mr^2 \quad (12)$$

$$E = \frac{1}{2} mr^2\omega^2 \quad (13)$$

FES systems divided into two categories in terms of their speed ; a heavy rotor made from steel referred to as Low Speed Flywheel (<6000 rpm) and light composite rotor referred to as High Speed Flywheel (<100000). While low speed flywheel has a specific power rate of almost 5 Wh/kg, high speed flywheel's specific power rating is up to 100 Wh/kg. Energy density depends on shape of flywheel as well. Choice of the material with light weight and high tensile strength plays a significant role in system performance [28].

FES systems have power capacity of 0.1-20 MW, energy capacity of 0.025-5 MWh and 90-95 % efficiency. FESs have more than 20000 cycling times and nearly 20 years as lifetime [13, 19, 32]. Fast response time, long lifetime and high cycling times bring FES systems to the suitable position for power quality applications [27]. In Canada, 10 flywheels with 5 MW power capacity installed in order to support power quality in a 20 MW WPP [26].

Hourly self discharge rate of FES is 20% and with that reason it is used in small scale applications. Magnetic bearings and frictional losses are the main reasons for decreasing its efficiency. Due to the high cost of the composite materials it contains, it is not yet suitable for large scale applications [27].

Recently researchers work on rising specific power, increasing speed of rotor and decreasing self discharge rate [27].

VII. DISCUSSIONS

With the going in effect of Kyoto Protocol, interest in environmentally friendly renewable energy sources has raised. According to EIA's (Energy International Administration) report, worldwide share of renewable electricity generation in 2012 is 22%, but in 2040 it is estimated that this value will be %29 [7]. However, as a result of increasing penetration of WPPs into the grid, which is more than %20, can lead to problems, given in Table 5,that can be gathered under the headings of power quality, bridging power and energy management. To minimize these issues, the most promising possible solution is Energy Storage.

TABLE V. APPLICATIONS OF ENERGY STORAGE SYSTEMS IN WPPS [33]

Applications Name	Example Applications	Discharge Time Required
Power Quality	Transient Stability, Frequency Regulation	Seconds to Minutes
Bridging Power	Contingency Reserves, Ramping	Minutes to ~1 hour
Energy Management	Load Levelling, Firm Capacity, T&D Deferral	Hours

Discharge time of the storage type is important to resolve the power quality, bridging power and energy management problems. Information about the discharge times of the systems is given in Table 6.

TABLE VI. CHARACTERISTICS OF ENERGY STORAGE SYSTEMS [13, 14, 19, 32]

Technology		Power Rating (MW)	Energy Rating (MWh)	Discharge Time	Response Time	Cycling Capacity	Efficiency (%)	Daily Self-Discharge (%)
PHES		30-4000	500-8000	1-24h+	minutes	20000-50000	75-85	very small
CAES		50-300	500-2500	1-24h+	minutes	10000-30000	64-75	small
Batteries	**Lead-acid**	0.01-10	up to 40	seconds to hours	miliseconds	500-2000	70-90	0.1-0.3
	Ni-Cd	0.01-40	up to 6.75	seconds to hours	miliseconds	2000-3000	60-80	0.2-0.6
	NaS	0.01-34	0.01-1200	seconds to hours	miliseconds	2500-4500	75-90	very small
	Li-ion	0.01-100	0.004-10	minutes to hours	miliseconds	1000-20000	90-95	0.1-0.3
HES		0.1-50	up to 120	seconds to 24+	seconds	20000+	35-40	small
FES		0.1-20	0.025-5	seconds to 15 min	seconds	20000+	90-95	100

For power quality applications, energy storage methods such as LA, NiCd, li-ion and flywheel are used because of their discharge durations. Nickel cadmium, lead acid and lithium ion have discharge times in the order of minutes to hours. By this specification these batteries become preferable for bridging power applications. For load leveling, firm capacity, transmission and distribution deferral applications PHS, CAES and NaS batteries are generally used.

TABLE VII. FEATURES OF ENERGY STORAGE SYSTEMS [14, 19, 32]

Technology		Energy Type	Maturity	Suitable Storage Duration	Enviromental Concerns
PHS		Mechanical	Mature	Hours-Months	Destructions of trees and green land
CAES		Mechanical	Commercialized	Hours-Months	Emissions from combustion of natural gas
Batteries	**LA**	Electrochemical	Mature	Minutes-Days	Chemical disposal issues
	Ni-Cd	Electrochemical	Commercialized	Minutes-Days	Chemical disposal issues
	NaS	Electrochemical	Commercialized	Hours-Months	Chemical disposal issues
	Li-ion	Electrochemical	Demonstration	Minutes-Days	Chemical disposal issues
HES		Chemical	Developing	Hours-Months	Combustion of fossil fuel
FES		Mechanical	Early Commercialized	Seconds-Minutes	Slight

By using Table 5, 6 and 7 in comparing the characteristics of energy storage systems:

- PHS and CAES are suitable for large scale applications due to their high power capacities (>100 MW) and high storage duration (hours – months).
- PHS, CAES and promising technology HES have low self-discharge rate so these methods are appropriate for long scale energy storage and firm capacity. In contrast to that, Flywheels have a daily self-discharge rate that is 100%, used for only short scale storage.
- Lead acid and nickel cadmium batteries' low cycle life make them useful for power quality and bridging power applications.
- Geographical conditions and size of the systems are critical factors on selection of ES systems. Researches on batteries have increased recently by the reason of difficulties on CAES and PHS's geographical selection and long construction duration.

In this study a number of different ES technologies are compared and discussed in order to decide the suitable technology for desired conditions.

VIII. CONCLUSIONS

In this paper, emerging methods of ESS, such as PHES, CAES, Batteries, HES and FES, are discussed by working principles, applications on WPPs and characteristic features in order to overcome the problems that occurs due to the intermittent and variable nature of WPPs integration on the grid. Although there are a number of ES methods to clear up the difficulties (power quality, bridging power, energy management) caused by integration of WPPs to the grid, the crucial target is to meet the demands simultaneously. To achieve this goal, ESS such as lithium batteries and HES are expected to be a significant part of this process in the future.

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