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Characteristics and Applications of Energy Storage System to power network - A review

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Abstract

Maintaining reliability and stability of a power systems in transmission and distribution level becomes a big challenge in present scenario. Grid operators are always responsible to maintain equilibrium between available power generation and demand of end users. Maintaining grid balance is a bigger issue, in case of any unexpected generation shortage or grid disturbance or integration of any renewable energy sources like wind and solar power in the energy mix. In order to compensate such imbalance and to facilitate more renewable energy sources with the grid, energy storage system (ESS) started to be playing an important role with the advancement of the state of the art technology. ESS can also help to get reduction in greenhouse gas (GHG) emission by means of integrating more renewable energy sources to the grid. There are various types of Energy Storage (ES) technologies which are being used in power systems network from large scale (above 50MW) to small scale (up to 100KW). Based on the characteristics, each storage technology has their own merits and demerits. This paper carried out extensive review study and verifies merits and demerits of each storage technology and identifies the suitable technology for the future. This paper also has conducted feasibility study with the aid of E-Select™ tool for various ES technologies in applications point of view at different grid locations. This review study helps to evaluate feasible ES technology for a particular electrical application and also helps to develop smart hybrid storage system for grid applications in efficient way.

Keywords: Energy Storage System (ESS), Renewable energy, ESS characteristics, ESS applications, Feasibility

1. Introduction

Energy storage system (ESS) means that a device or system stores energy in any form and delivers energy in same or different form according to requirement of applications. ESS plays an important role in modern power system to fulfill the following applications: load leveling, peak shaving, provides support for grid stability and reliability, and provides better energy and power management that improves the overall power quality (PQ). ESS also mitigates integrating challenges of renewable energy (RE) sources into the grid. Above 50 MW used as bulk storage or spinning reserve in generation level, upto 10 MW is used as medium storage in transmission and substation level, from 2 MW to 100 KW is used as small storage in commercial low voltage distribution network [1-3]

Depends on the type of mechanisms used for storing energy, ESS can be classified into (i) Mechanical ; Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), Flywheel Energy Storage (FES), (ii) Electrical ; Super Capacitor (SC), Super Magnetic Energy Storage (SMES), (iii) Electro chemical ; Secondary batteries, redox flow batteries, (iv) Chemical ; Hydrogen and other gas storage, (v) Thermal ; Thermal Energy Storage (TES) [4]

PHES system is a matured and large scale energy storage technology which is the same as to conventional hydroelectric power system. It is a long life storage system with efficiency of around 70% to 85%. CAES technology is in the category of large scale energy storage technology, consists of a compressor, gas turbine and high pressure air storage tank. The efficiency for CAES is around 70% to 80%. [4, 5]. FES is a mechanical type storage system, stores energy in the form of kinetic energy. Self-discharge loss of FES is high during idle condition [4, 6]. SC stores energy in the form of electric field between a pair of electrode charge plates. SC is having the capability of rapid charge and discharge behavior with higher life time. Efficiency of SC is around 85% to 98% with higher lifetime [6]. SMES stores energy in magnetic field when direct current flows through super conductive coil. SMES system efficiency is around 90% to 95% and it can be used for power quality applications in power system network [4]. Secondary batteries or rechargeable batteries are working on the principle of electro chemical technology. Secondary batteries like; Lead acid (Pb acid), nickel cadmium (Ni-Cd), nickel metal hydride (Ni-MH), sodium sulphur (NaS), sodium nickel chloride (Na-Nicl), lithium ion(Li-Fe), metal air are belongs to electro chemical storage technology [7]. Flow battery storage system, stores and release energy through reversible electro chemical reaction between two electrolytes. Flow batteries life time is more with the efficiency of around 70% to 75%. Hydrogen is available in water, organic materials, biomass and hydrocarbons. Hydrogen storage energy density is higher as compared to other storage technologies. Hydrogen storage efficiency is low, only around 29% to 49% due to involving of more energy conversion process. TES provides long duration with high efficiency of storage at affordable cost [4]. In this paper, merits and demerits of various storage technologies have been verified, through extensive review study. Also feasible review study of various storage technologies have been carried out in applications point of view [2].

2. Characteristics of Energy Storage (ES) technologies

Characteristics of energy storage technologies are determined by the following factors; energy density, power density, round trip efficiency, response time, discharge duration, life time, self-discharge, technical maturity, cost, recharge time, operating temperature, memory effect, footprint (space and weight), environment impacts. [1, 4, 6]

2.1. Power density Versus Energy density

Specific power density is a relation between power to weight ratio that is maximum amount of power can be supplied per unit mass (w/kg). Specific energy density is a relation between energy to weight ratio that is amount of energy can be stored per unit of mass (wh/kg). Higher the power and energy density, reflects lighter in weight and smaller in size for a storage technology. PHES, CAES and Redox Flow Battery (RFB) are belongs to low energy density type as compared to other types. SMES, FES and DLC are belongs to high power density. Li-ion storage is a high power and high energy density type, which is more suitable for mobile storage applications. H2 and Synthetic Natural Gas (SNG) storage are belonging to high energy density type, suitable for long term storage applications. Fig. 1and Fig. 2 shows the relationship between power and energy densities of ES technologies[6].

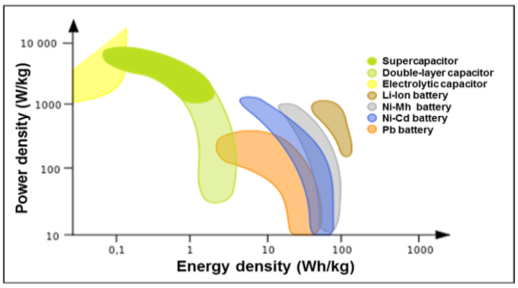

Fig.1: Power density versus energy density

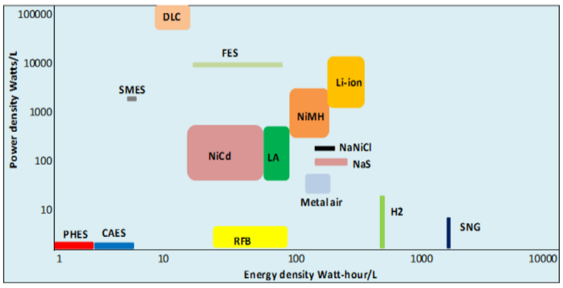

Fig.2. Volumetric power and energy density [6]

2.2. Round trip efficiency

Round trip efficiency (RTE) is also called as cycle efficiency. RTE is the ratio between energy output to energy input during one full (charge/discharge) cycle. RTE depends on the amount of losses occurs during charge, discharge and storing process. The loss of energy is expressed as in percentage (%) known as RTE. Equation-1 shows the efficiency relationship between energy in (E_{in}) and energy out (E_{out}). Fig. 3 shows the RTE of various storage technologies [6, 8].

$$\eta = E_{out} / E_{in} \qquad (1)$$

From the Fig. 3, Flywheel, SMES, DLC are having high RTE in the range of 85% to 98% as compared to other type of storage technologies. Li-ion storage technology RTE is also high in the range of 90% to 98%, whereas H2 storage technology RTE is only 49% maximum, due to involving of more energy conversion process.

2.3. Response time

Response time means amount of time required to start delivers power by a storage system, which is time required from no discharge to full discharge. Conventional batteries; lead acid (pb-acid), nickel cadmium (Ni-Cd), nickel metal hydride (Ni-MH) and advanced batteries; lithium ion (Li-ion), sodium sulphur (NaS), sodium nickel chloride (Na-NiCl) are belongs to quick response type storage technology. Flow batteries response time is less than in millisecond, whereas flywheel, SMES, double layer capacitor (DLC) are also belongs to quick response type storage technology as compared to CAES, PHES and hydrogen storage technologies. Fig. 4 shows the response time details of various storage technologies [6, 8].

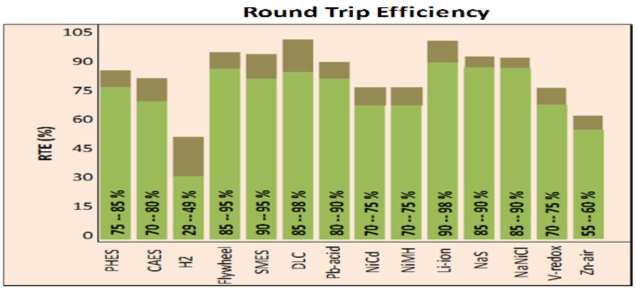

Fig.3. Round trip efficiency

Response time

Energy Storage Technologies	Response Time
CAES	1--15 minutes
PHES	Sec--minute
Hydrogen	ms--minute
Flywheel	ms--sec
Li-ion	ms--sec
SMES	ms
DLC	ms
Pb-acid	ms
NiCd	ms
NiMH	ms
NaS	ms
NaNiCl	ms
Zn-air	ms
V-Redox	< 1ms
Zn-Br	< 1ms

Fig.4. Response time [6]

2.4. Discharge duration

Discharge duration of storage technology depends on the power and energy density characteristics. High power density storage technologies; SMES, DLC and Flywheel can be used for power related applications, which are able to deliver at high power for short duration. PHES, CAES, Hydrogen storage technologies discharge duration is in the range of around hours to days. Flow batteries; V-Redox, Zn-Br discharge duration is around seconds to hours. Conventional and advanced batteries discharge duration is around minutes to few hours. Fig. 5 shows the power rating versus discharge duration of various storage technologies [6].

2.5. Self-discharge

If energy storage systems kept in charge for extended period without use that tend to lose some of its stored energy due to its self-discharge characteristics. Self-discharge level of each storage technology varies according to type of storing mechanism. Fly wheel self-discharge is around 20 to 100% per day, whereas DLC is around 2 to 40%. Lead acid battery storage self-discharge is around 0.1 to 0.3%, whereas for Ni-Cd is around 0.2 to 0.6%. NaS, Na-NiCl and SMES self-discharge is around 10 to 20%, while flow batteries having 1% per hour. PHES and CAES technologies are having almost negligible rate of self-discharge. Fig. 6 shows self-discharge level of ES technologies [6, 8].

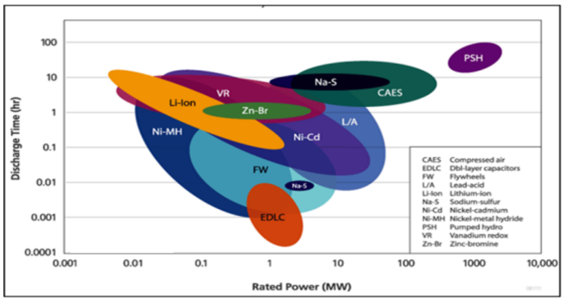

Fig.5. Rated power versus Discharge duration

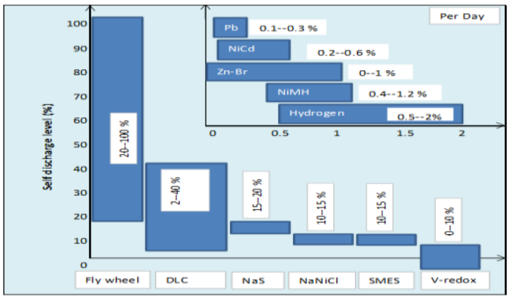

Fig.6.self-discharge level [6, 8]

2.6. Life time

All energy storage system downgrades over certain period of usage. Storage system life time depends on the following two criteria; calendar life: storage system in service for number of years, cycle life: number of charge and discharge cycles, in which storage system capable to tolerate before failure. Life time of storage system depends on the type of storage technology, operational parameters and other environmental conditions. From the below Table 1, life time related to both calendar years and number of cycles for PHES, CAES, SMES, Flywheel, DLC storage technologies are high as compared to other storage technologies [6, 8].

Table 1. life time of ES technologies [6, 9]

ES technologies	Calendar years	Number of cycles
PHES	40--60	12000--35000
CAES	25--40	9000--20000
SMES	> 20	10000
Flywheel	> 20	> 100000
DLC	> 20	> 500000
Ni-Cd	15--20	1500
Li-ion	8--15	> 4000
Pb-acid	3--15	2000
Ni-MH	5--10	300--500

NaS	12--20	2000--4500
Na-NiCl	12--20	1000--2500
Zn-air	30	> 2000
V-Redox	15--20	> 13000
Zn-Br	5--10	> 2000
Hydrogen	5--15	> 1000

2.7. Recharge time

Recharge time or charge rate is a rate at which the storage system can be charged. Most of the storage system charge rate is same as discharge rate. In some cases, charge time varies as rapid or slow that depends on the capacity of power conditioning unit, chemical reaction and type of storage medium. If a storage system not getting charge quickly, it cannot provide for next cycle of service. Fig. 7 shows the recharge time of various storage technologies [6, 9].

2.8. *Technical maturity*

Technical maturity of storage technologies can be classified into three categories; fully mature, medium mature, early and develop mature technology. PHES and lead acid battery are fully mature technologies, available for high and medium power range of applications. CAES, flywheel, SMES, DLC, Ni-Cd, Li-ion, NaS, Na-NiCl and flow batteries are belongs to medium or developed mature technologies. Ni-Cd, Ni-MH, Li-ion and Na-NiCl batteries can be considered as fully mature technology in case of portable or mobile applications. Metal air batteries, hydrogen storage with fuel cell are an early and develop mature technologies. Fig. 8 shows technical maturity level of various storage technologies [6]

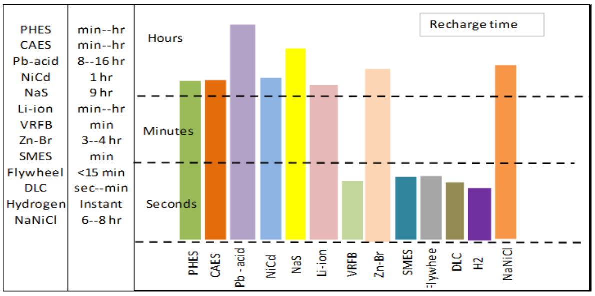

Fig.7. Recharge time

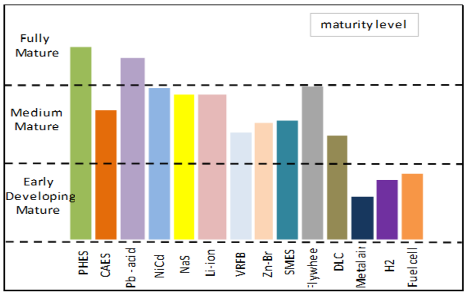

Fig.8. Maturity level[6]

2.9. Cost

Cost of energy storage technology involves mainly in two parts; capital, life cycle cost. Total capital cost includes energy cost ($/kWh) of storage unit, power cost ($/kw) of balance of sub system, like power conversion system (PCS). Life cycle cost includes operation and maintenance cost, electricity cost for recharging, fuel cost (for CAES) and replacement cost. As per energy capacity cost of concern, SMES, Flywheel and DLC are having the highest investment cost. NaS batteries are having high operation and maintenance cost, while Pb-acid battery comes in second level [6]. Equation-2 shows the relationship details of levelized cost energy ($/kwh) of a storage system [3, 9-11].

$$\text{Cost Of Energy (COE)} = (AC + OMC + ARC) / AED \qquad (2)$$

$$\text{Annual energy discharge (AED)} = P*n*H*D \qquad (3)$$

(Where AC = annual capital cost, OMC = annual O&M cost, ARC = annual replacement cost, P= rated power capacity of storage, n = charge/discharge cycles per day, H=length of each discharge cycle duration, D = annual operating days of storage).

2.10. Operating temperature

Operating temperature varies according to type of storage technologies characteristic. DLC can operate in wide range of temperature from -45^{0}C to 85^{0}C. NaS battery operating temperature is high around 300^{0}C, while SMES temperature is extremely very low. Na-NiCl and Ni-Cd operating temperature is in the range of -40^{0}C to 70^{0}C, while Pb-acid operating temperature is around 27^{0}C. If Pb-acid battery operating temperature rises in excess of 5^{0}C (from 27^{0}C) can reduce life time of around 50%. CAES and PHES system can operate at ambient temperature [6]

2.11. Foot print

Area of space required per unit energy capacity of a storage unit is called as foot print or spatial requirement which is expressed in m^2/kwh. It is closely related with energy and power density of storage system. Hydrogen storage system have least space required per unit of energy storage, that is around 0.005 to 0.05 m2/kwh, while Zn-air battery storage space requirement is around 0.005 m2/kwh. PHES and CAES system are occupying large area and volume as compared to other storage technologies [6, 8].

2.12. Memory effect

It means that a battery repeatedly recharged after being only partially discharge. This effect occurs mostly in Ni-Cd and NiMH batteries. This will cause loosing of maximum energy storage capacity of battery gradually. By making full charge and full discharge of a battery once in a month can helps to mitigate this effect [6, 7].

2.13. Environment impacts

Battery energy storage leads to prone toxic and corrosive due to usage of certain metals as electrodes and acid as electrolyte. In Lead acid battery, lead as a toxic metal and sulphuric acid creates corrosive atmosphere, whereas for nickel cadmium batteries, cadmium is highly toxic material. For li-ion batteries, less environment impact as compared to other batteries, since lithium oxide and salt can be recycled easily. CAES type needs large underground space with high pressure air storage which make impacts for environment, whereas PHES technology needs specific geological formations. For flywheel storage, no chemical impact on environment but stringent safety guards is necessary while in operation [4, 6, 7].

3. Applications of ESS

ESS can be used to support electrical power system from large scale to small scale applications. ESS can be used to move or shift electricity through time, delivers when and where it is required. ESS helps to balance and smooth out fluctuations of Renewable Energy (RE) generation with proper deployment and integration into grid. Also ESS can be used to support grid reliability and asset utilization. Usage of ESS can be considered in five locations of power system. Fig. 9 shows the details of different ES Technologies usage in various locations of power system [2]. Usages of ESS in various applications are summarized below [2]

Storage Technologies	Central or Bulk	Sub-station (requiring assembly)	Container / CES Fleet	Comm-ercial / Industrial	Res-idential / Small Comm-ercial
Lithium-ion - High Power	✓	✓	✓	✓	✓
Lithium Ion - High Energy	✓	✓	✓	✓	✓
Ni batt. (NiCd, NiZn, NiMH)		✓	✓	✓	✓
Advanced Lead Acid	✓	✓	✓	✓	✓
Valve Regulated Lead Acid	✓	✓	✓	✓	✓
Vanadium Redox Battery	✓	✓	✓	✓	
Adv.Vanadium Red. Flow Batt.	✓	✓	✓	✓	
Zinc Bromide	✓	✓	✓	✓	✓
Sodium Sulfur	✓	✓	✓	✓	
Sodium Nickel Chloride	✓	✓	✓	✓	✓
Thermal Storage (Cold)		✓		✓	✓
Thermal Storage (Hot)				✓	✓
Zinc- Air Battery		✓	✓	✓	✓
Flywheel	✓	✓	✓	✓	✓
Double Layer Capacitors	✓	✓	✓	✓	
Hybrid LA & DL-CAP	✓	✓	✓	✓	✓
Compressed-Air ES, cavern	✓	✓			
Compressed-Air ES, small	✓	✓	✓	✓	
Pumped Hydro	✓				

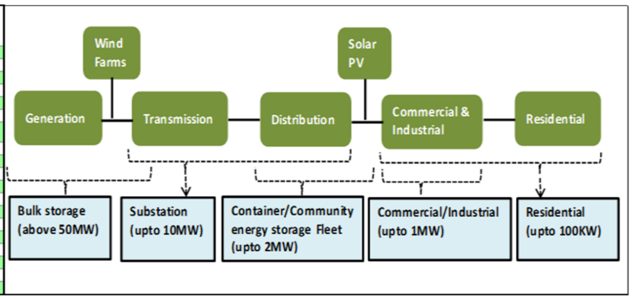

Fig.9. Usage of ES technologies in various grid location[2]

3.1. Energy time shift (arbitrage) and supply capacity

By moving or shifting electricity through time to get benefits of price difference during on peak and off peak period. That is purchase of electricity during low demand at low price to store in storage system and delivers during high demand at high price in wholesale network market place [1-3]. ESS helps to save additional investment cost by means of substitute or defer development of new power generation capacity in wholesale network market place [1-3].

3.2. Load following and supply reserve capacity

ESS can be used for load following services by varying its output energy to balance generation and load at particular area of power system network [1-3]. ESS can be used as supply reserve capacity or standby generation capacity that can be ready to called up in case of any sudden or unexpected generation loss [1-3].

3.3. Transmission support and congestion relief

ESS can be used for this ancillary service to support grid stability. ESS provides both real and reactive power with standard discharge duration of around 2 to 5 seconds in the range for this service [1-3]. Transmission congestion occurs when there is any shortage of transmission line capacity due to transmission of excess power at peak demand. ESS can store electricity during off peak with no congestion hours and release during peak congestion hours [1-3].

3.4. Electric service reliability and power Quality

ESS provides high reliable service in power system at industrial and commercial level in case of any power outage for extended period. ESS can be used to reduce power quality related financial losses at utility end users level. Suitable storage system can be used to mitigate power quality issues related to voltage or frequency variation during the case of any network disturbance [1-3].

3.5. Renewable integration

- *Wind and solar energy time shift (arbitrage) and renewable energy smoothing:* By moving or shifting stored excess wind energy through time from low demand to high demand periods. ESS can be used for wind and solar energy time shift application, which benefits overall cost of electricity, enables transmission relief for wind and solar farm. Wind and solar power generation varies frequently and highly intermittent in nature. ESS can be used to smooth out such variation of solar and wind power output and ensures reliable operation [1-3]

- *Renewable energy capacity firming:* Solar and wind power output intermittency can be classified into short duration (randomly varies from seconds to minutes) and diurnal (regular variation during 24 hours). Such output variation of solar and wind power is firmed into constant by using suitable storage system. RE capacity firming is effective when there is peak demand occurs in power system [1-3].

As per DOE international energy storage data base [12], as an example, NaS storage system under operational since 2012, at Vaca Dixon Solar Plant, Vacaville, California (US) with rated capacity of 2MW and with 7hrs discharge duration used for the following applications; Renewable energy time shifting, Renewable capacity firming, load following, frequency regulation, supply reserve capacity [12].

4. Feasibility study of ES technologies

4.1. Feasibility Analysis

In this section, feasibility analysis of various storage technologies has been carried out with the help of ES-Select™ tool. The ES-Select™ tool was developed by DNV-KEMA in collaboration with Sandia national Laboratories. ES-Select™ tool software is useful to study feasibility comparison between various ES technologies in simple and visual form [2]. Feasibility scores for each storage option is estimated on the basis of four criteria; Maturity (commercial usage), appropriate grid locations (considering availability, size, weight, scalability, mobility), application requirements (Considering discharge duration, cycle life, efficiency), Installed cost (considering either $/KW or $/KWH) [2].

ES-Select™ considers only six numbers of applications at a time. Therefore, to determine the feasibility scores of ES technologies, two groups related to bulk storage application were considered for generation and transmission level application and renewable applications. Six numbers of applications are selected in each group to find out relative feasibility scores of appropriate ES technologies [2]. For group-1 considered the following applications; Energy time shift, Supply capacity, Load following, Area regulation, Supply spinning reserve, Transmission congestion relief. For group-2 considered the following applications; Wind and solar energy time shift, wind and solar energy smoothing, renewable capacity firming, black start. Fig. 10 and Fig. 11 shows the feasibility scores and feasibility factors of applicable ES technologies for the following (group-1) applications; energy time shift, supply capacity, load following, area regulation, supply spinning reserve and transmission congestion relief [2]

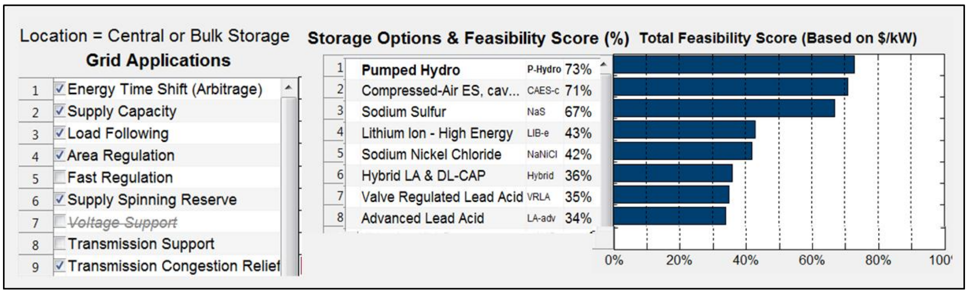

Fig.10. (Group1) feasibility scores of ES technologies [2]

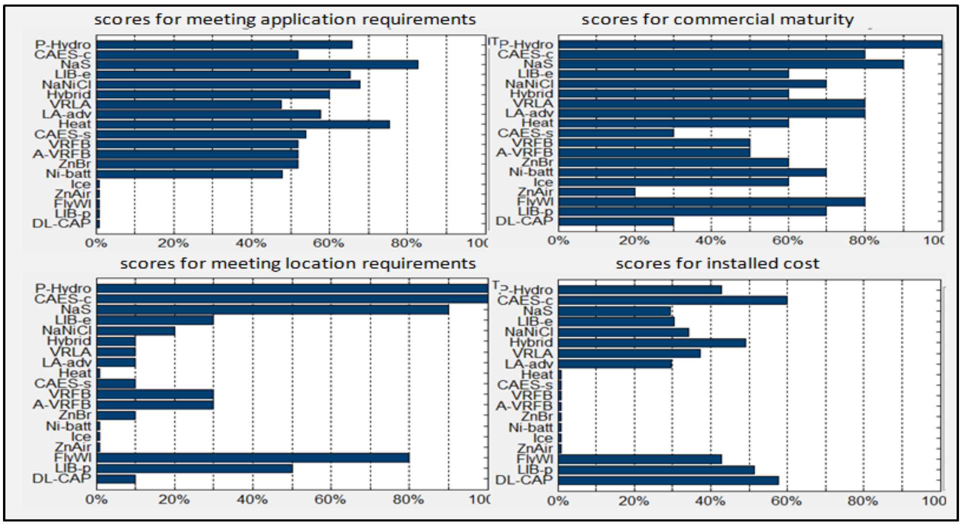

Fig.11. (Group1) feasibility factors of ES technologies [2]

Fig. 12 and Fig. 13 shows the feasibility scores and feasibility factors of applicable ES technologies for the following (group-2) applications; wind and solar energy time shift, wind and solar energy smoothing, black start.

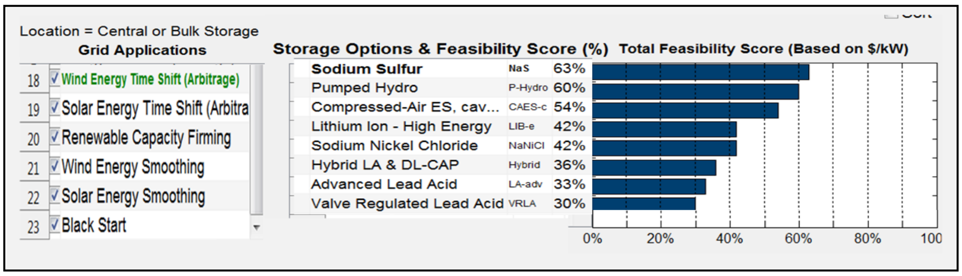

Fig.12. (group-2) feasibility scores of ES technologies[2]

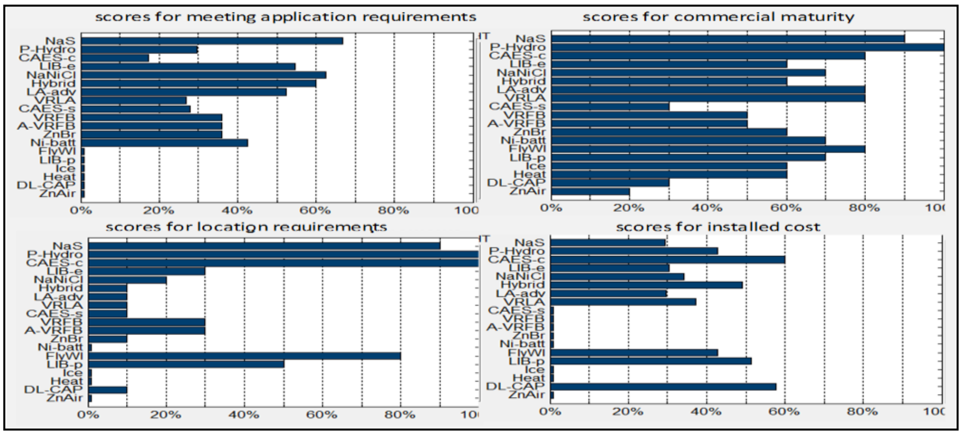

Fig.13. (group-2) Feasibility factors of ES technologies[2]

From the above feasibility study, Fig. 10 clearly shows that PHES (73%), CAES (71%) and NaS battery (67%) are more feasible while lead acid battery is less feasible (34%) for group-1 applications; energy time shift, supply capacity, load following, area regulation, supply spinning reserve and transmission congestion relief. Similarly Fig. 12, shows that NaS battery (63%), PHES (60%), CAES (54%) are highly feasible whereas valve regulated lead acid battery (30%) is less feasible for group-2 applications; wind and solar energy time shift, wind and solar energy smoothing, renewable capacity firming, black start [2].

4.1.1. Feasibility scores of ES options for various grid locations

The overall feasibility study of ES technologies used for all five grid locations; residential/small commercial, commercial/industrial, containers/Community Energy Storage fleet (CES), substations, central/bulk are detailed in Fig. 14. In Fig. 14, the feasibility score considered in the scale range of between 0 to 1. Feasibility score of ES technologies around 1 or near to 1 is considered as highly feasible [2, 3].

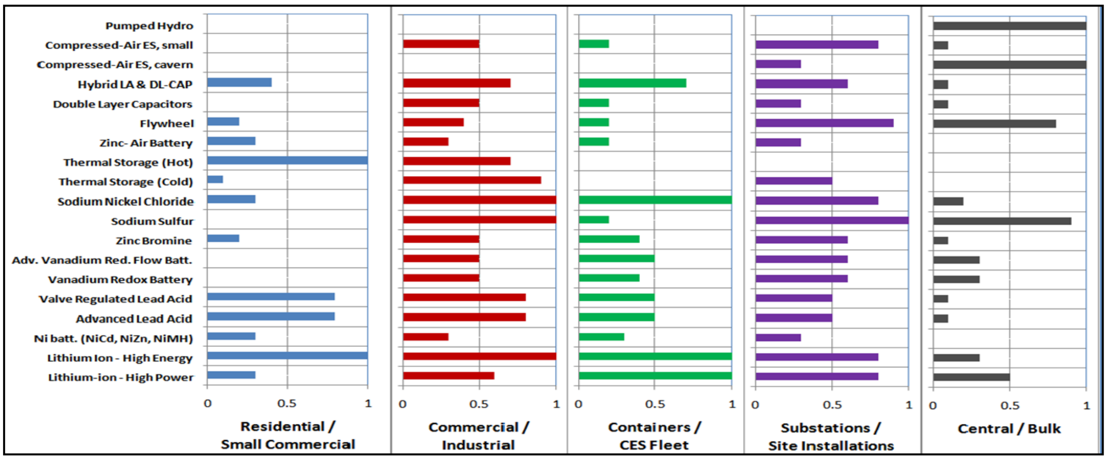

Fig.14.Feasibility scores of ES options in various grid locations [3]

From the above Fig. 14, clearly shows that thermal storage (hot), li-ion high energy, lead acid battery technologies are more feasible for usage in residential and small commercial level (upto 100KW) applications, whereas for commercial/industrial applications (upto 1MW), Na-NiCl, NaS, Li-ion high energy batteries are more feasible. Similarly for containers/CES fleet location (upto 2MW), NaNiCl, Li-ion battery technologies are more feasible, whereas for substation level (upto 10MW) NaS, flywheel, Li-ion storage technologies are more feasible. For bulk storage applications (above 50MW) PHES, CAES, NaS storage technologies are more feasible [2, 3].

5. Conclusion

This study carried out an extensive review on current ES technologies and explores their characteristics and application services. Based on their characteristics, some of the storage technologies are more feasible for a particular application while some other storage technologies are suitable for other applications. For example flywheel, super capacitor and SMES are high power density type, suitable for the power quality applications, whereas Li-ion battery storage is having the characteristics of high power and high energy density, suitable for T&D support as well as power quality and electric vehicles applications. From the feasibility study with the aid of ES-Select^{TM}, it clearly shows that PHES and CAES are more feasible for bulk storage applications at generation and transmission level (more than 50MW) while NaS battery storage is feasible for T&D (substation) level (upto 10MW) applications. Due to higher efficiency, Li-ion is more feasible for distribution, commercial/industrial and residential level applications (from 10MW to 100KW) whereas Na-NiCl storage is highly feasible for distribution and commercial/industrial level applications. Thermal storage (hot) is more feasible for residential application. This study requires further research and development in the following directions for deployment of a smart storage system:

- Research and study in depth is required to develop smart hybrid energy storage system
- Further research study is required to develop feasible, smart ESS for smart grid and micro grid applications
- Further study and development of smart control system to integrate reliable ESS in Micro grid.

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