# Electrical Energy Storage Systems: Technologies' State-of-the-Art, Techno-Economic Benefits and Applications Analysis

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## Abstract

*Nowadays, with the large-scale penetration of distributed and renewable energy resources, Electrical Energy Storage (EES) stands out for its ability of adding flexibility, controlling intermittence and providing back-up generation to electrical networks. It represents the critical link between the energy supply and demand chains and, moreover, a key element for increasing the role and attractiveness of renewable generation into the power grid, providing numerous technical and economic benefits to the power system stakeholders. On islanded systems and micro-grids, being updated about the state-of-the-art of EES systems and their benefits becomes even more relevant. Hence, in the present paper a comprehensive analysis of EES leading technologies' main assets, research issues, global market figures, economic benefits and technical applications is provided.*

## 1. Introduction

In the past, power systems utilities have operated in its simpler form via one-way transportation from large power plants distant from the point of consumption. With the introduction of distributed and renewable energy resources, Electrical Energy Storage (EES) applications (after long disregard) are making a comeback, upon the recognition and technological advancement of its role in adding flexibility, controlling intermittence and provide uninterruptible power supply to the network [1].

Electric power is a commodity that may be wasted if it is not preserved or consumed. In particular, the electricity generated using renewable energy resources (such as solar and wind generation, which do not work all the time and have huge fluctuations due to their stochastic nature) is difficult to adjust in response to the demand needs. Therefore, storage means are needed to avoid stability problems [1]-[3], since it is not feasible anymore to consider building more inefficient, over-designed and expensive power plants as an ultimate solution. Being the main advantage of EES systems the release of additional capacity to the grid when it is valuable, their numerous applications will strengthen power networks and maintain load levels even during critical service hours. As a result, EES systems represent the critical link between the energy supply and demand chains, standing as a key element for the increasing grid integration of renewable energies, as well as for distributed energy generation spread and stand-alone power systems feasibility. Moreover, in a broader sense, EES will enable the Smart Grid concept to become a reality.

Electricity supply in combined conventional and decentralized grids using renewable energy resources requires affordable and reliable power management mechanisms, including sustainable storage systems, despite of some drawbacks in storage systems applied to electricity, related to the type of technology and operating costs [4], [5]. Several storage technologies have been developed with different response characteristics, and the state-of-the-art of these EES systems, their benefits and their applications have been reviewed and analyzed throughout this paper.

In particular, on islands' power systems, there are some additional challenges to face. Under a large-scale renewable penetration scenario, being remotely located and not electrically connected to other grids, EES applications along with efficient management of the distribution networks take an even more important roll. Thus, special emphasis must be given to EES on islands, studying their particular requirements and the most appropriate technologies.

## 2. Description of Electrical Energy Storage

### 2.1. Basic EES principles

EES, as shown in Figure 1, refers to the process of converting electrical energy from a power source or network via an energy conversion module (ECM) into another form or energy storage medium (ESM), such as chemical, mechanical, thermal or magnetic.

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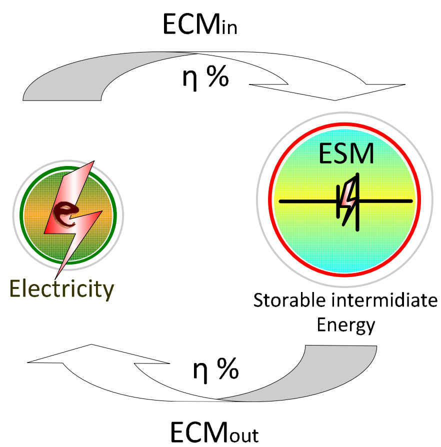


**Figure 1. EES cycle schematic representation**

This intermediate energy is stored for a limited time in order to be converted back into electrical energy when needed [1]. The roundtrip efficiency of the EES system is reduced by both energy transformation processes inherent efficiencies and storage losses.

An EES is characterized by many features related to its electrical capacity, efficiency, charge/discharge behaviour, lifetime, cost and environmental/location issues. Some of these characteristics are intimately related to each other. For instance, in some technologies, particularly lead-acid batteries, the depth-of-discharge is critical and can shorten or enlarge their lifetime. Most relevant features of ESS are discussed and defined for existing technologies later on section 3 on this paper.

The study of EES technology suitability is carried out taking into consideration all features, to the benefits of different power system parties/stakeholders (from utilities to end-users).

## 2.2. Benefits of using EES

Basically EESs benefits can be classified into two generic categories that make electricity storage interesting. On the one hand, high energy EES would help improving profitability, i.e., it secures economic benefits to the power system stakeholders. On the other hand, high power EES provide reliability, safety and productivity, i.e., it provides technical benefits. Furthermore, this classification is not compulsory whatsoever, being possible to find high profitability on high power applications and vice-versa.

At the same time, these power and energy benefits may be classified according to what they provide to the power system stakeholders, economic savings/revenues or technical enhancements.

### 2.2.1. Technical Benefits

The most relevant technical benefits of EES are the following:

a) Bulk energy time-shifting, for load leveling and peak shaving, providing electricity price arbitrage. For instance, electric vehicles represent one type of EES that can provide these power management benefits, leading to smart grid and RES integration.
b) EES may play an important role in the integration of renewable energy into the grid [2].
c) More efficient use and contribution of renewable energy is guaranteed using EES, also fomenting the use of distributed energy supply options in grids.
d) Several base-load generation plants are not designed for operation as part load or to provide variable output. However, storage may provide attractive solution to these drawbacks by setting the optimal operation point, rather than firing standby generators. In addition to that, EES have superior part-load efficiency [6].
e) Efficient storage can be used to provide up to two times its capacity for regulation applications; using full charge (down) and full discharge (up).
f) Storage output can be changed rapidly giving a ramping support and black-start to the grid (from none to full or from full to none within seconds rather than minutes) [6].
g) EES is a practical way to provide transmission congestion relief [3].
h) Energy storage can be used as a solution for improving grid service reliability.
i) There are always ideal locations for portable EES in a distribution system. On top of that, these systems can be also relocated so that after a certain number of years, when an upgrading of the system is performed, portable EES can be moved and used to perform the same function again [3].
j) Energy storage can benefit utilities or independent system operators allowing transmission and distribution upgrade deferrals.
k) EES can serve as a stand-by power source for substations on-site and distribution lines, or to add transformers.
l) In the near future, ESS technologies may facilitate other non electrical energy uses, like transportation and heat generation.

### 2.2.2. Economic Benefits

The most relevant economic benefits of EES are the following:

a) Energy storage can cut costs for customers of electricity.

b) In general, off-peak electricity is cheaper compared to high-peak electricity, and this also benefits the seller of electricity.
c) It plays a key role on stabilizing the electricity market price freeing the power sector from speculations and the volatility imposed by fossil fuels.
d) EES usage also overrides the need for peak generation, avoiding unnecessary additional cost burdens for generators.
e) It will contribute to the economic development and employment opportunities for many countries.
f) It will allow more efficient use of renewable and off-peak generation capacity, encouraging more investment opportunities on these technologies.
g) EES may help to avoid transmission congestion charges, which are very expensive and most of utilities try to avoid them in a deregulated market environment [3].
h) Reduces the need for transmission and distribution capacity upgrades, thus minimizing unnecessary investments.
i) Increases and improves availability of ancillary services, reducing penalties to generators and the cost of over dimensioning infrastructures.
j) Allows a market-driven electricity dispatch, fostering proactive participation of the customers to secure their benefits and creates a cost sharing scheme in the power system.
k) Storage tends to lower GHG and other emissions, reducing carbon cost. However this cost reduction is specific to the resource and varies greatly between technologies.
l) Compared to an average value for power-related installations under construction today, the cost of the storage components is relatively inexpensive.

More practical illustrations of the benefits of EES applications are, for instance: the Kaheawa wind power project II in Maaleea Maui Island, Hawaii, USA, since 2012, serving more than 145,000 persons (approximately 68,000 customers) with tourist and agricultural uses.

The peak demand for the site is nearly 195 MW, supplied using 72 MW of wind, 1.2 MW of PV and 290 MW of fossil fuels, as main sources of energy. The project uses a battery storage system based on advanced lead-acid battery with 10 MW of capacity and a rated discharge of 45 min, designed for applications to support nearly 21 MW.

It represents a significant portion of the wind farm output employed, including electric supply reserve, ramping and renewable capacity firming, among other benefits [7].

The Santa Rita jail smart grid project with a completion date in March 2012, launched by Alameda County and Chevron Energy Solutions, is another illustration of EES integration on onsite wind power, solar thermal, solar photovoltaic's, fuel cell cogeneration, using advanced EES systems with outstanding performance on the energy management system, increasing reliability and security.

The system comprises 2 MW (12 MWh) Lithium Ferrous Phosphate battery storage with a duration of 2 h at rated power and 1 MW fuel cell, 1.2 MW PV, 200 kW wind, and two 1 MW diesel generators to supply a 3 MW load, reducing the demand on the distribution feeder by 15 %.

Such system integration has improved significantly grid reliability, providing support to the electric distribution grid by providing dispatchable renewable energy, enabling seamless islanding and ensuring secure operation and cost reduction [8].

An additional illustration of the benefits of EES systems application is the Sodium Sulfur Battery (NAS) with a capacity of 1 MW at Catalina Island (Channel Islands of California, Pacific Ocean, USA), in operation since 2011.

This EES system is intended to guarantee grid-connected residential reliability, voltage support and supply support applications, thus improving energy quality at the end user side [7].

## 3. EES technologies' main assets and research issues

Main existing EES technologies are studied in this chapter, which covers cost, efficiency, electrical capacity, discharge behavior, lifetime, maturity and applications for each EES technology.

Moreover, their main assets along with the research issues are listed in the following epigraphs, in order of relevance.

### 3.1. Pumped-hydro energy storage (PHES)

Main assets:
- High power rating and energy storage capacity;
- Mature and widespread (over 99% of EES installed capacity);
- Low levelized cost of electricity (LCE);

Research issues:
- Pump-turbine head limits (700 m) at high speed;
- New PHES designs, such as the use of seawater as lower reservoir, tidal barrages, GPMES, Green Power Island concept, etc.

### 3.2. Compressed air energy storage (CAES)

Main assets:
- High power rating and energy storage capacity, comparable to PHES;
- Has quick response (secs-mins) and the afore mentioned large-scale features, being suitable for numerous power & energy grid applications;

Research issues:
- Relatively reduced round trip efficiency (RTE) related to cooling/heating processes;
- Turbine technology (high pressure turbine);
- Development of efficient thermal energy storage;
- Small-scale and Mini CAES for smaller applications;
- Advanced-adiabatic CAES (AA-CAES) technology.

### 3.3. Small-scale compressed air energy storage (SS-CAES)

Main assets:
- Installed above ground, avoiding conventional CAES geological requirements;
- No gas turbine required;
- Low pressure requirements for equipment;

Research issues:
- Development of portable units.

### 3.4. Thermal Energy Storage (TES)

Main assets (see Figure 2):
- High energy storage capacity (up to 2 GWh) and power rating (up to 200 MW);
- Scalable;
- Solar thermal being a zero emission and zero cost "fuel";

Research issues:
- New collector and storage mediums for high temperature solar thermal plants, phase change materials, etc.;

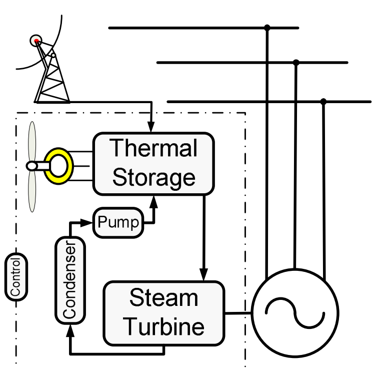


**Figure 2. TES simplified diagram**

- Reduce heat losses in storage, heat exchangers and pipes;
- High-temperature sensible heat storage with turbine is to be developed.

### 3.5. Hydrogen energy storage system (HESS)

Main assets (see Figure 3):
- Flexible technology as, once $H_2$ has been collected as a product of the electrolysis, it can be used as fuel for combustion engines or to serve as input along with $O_2$ for a fuel cell to produce electricity again;
- High energy mass density (100-1,000 Wh/kg);
- Suitable for energy & power applications, and due its scalability, it is defined as bridging;

Research issues:
- Scale-up limits;
- Development of fuel cells;
- Hydrogen storage materials.

### 3.6. Chemical energy storage system / Batteries (BESS)

Main assets:
- Almost instantaneous response (~20ms);
- Low initial capital cost for most mature BESS;
- There are numerous BESS technologies, the following ones outstanding as the most relevant:
  - Lead-Acid and Advanced Lead-Acid batteries;
  - Nickel-Cadmium batteries;
  - Nickel-Metal Hydride batteries;
  - Lithium-Ion batteries;
  - Sodium-Sulfur batteries;
  - Sodium Nickel Chloride batteries;
- They cover all power systems size needs and all the applications (except for baseload generation capacity)
- Modularity, scalability and portability

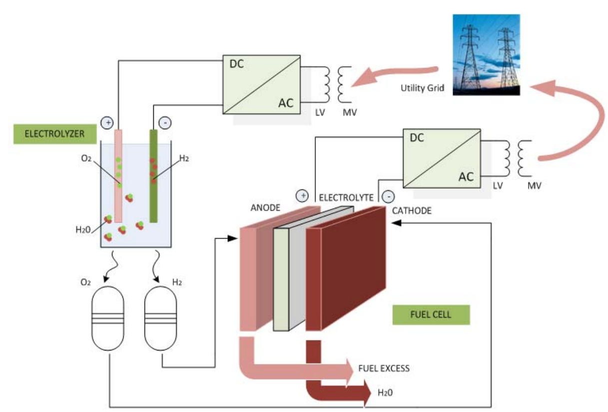


**Figure 3. Regenerative hydrogen fuel cell**

Research issues:

- Hazardous chemicals (Lead, Cadmium, Sulfurs…) disposal solutions;
- Batteries recycling;
- Development of efficient thermal energy storage devices;
- Most mature BEES Lead-Acid high density limitation, being improved at Advanced Lead-Acid batteries. However, others more efficient and lighter chemicals are being researched and tested for large-scale grid applications (i.e. Li-ion with up to 95% RTE and 245-2,000 W/kg).

### 3.7. Flow batteries energy storage (FBES)

Main assets:

- Higher discharge duration (up to 20 hrs) and energy storage capacity than conventional batteries;
- There are various technologies:
  - Vanadium Redox, the most mature;
  - Zinc-Bromine Redox, in test for commercial units;
  - Polysulfide Bromide Regenesys;

Research issues:

- Demonstration for utility applications for Vn Redox FBES;
- Research being carried out for ZnBr Redox FBES for over 100kW applications.

### 3.8. Flywheel energy storage system (FESS)

Main assets:

- Quick response time (~4ms);
- High RTE (80-95%);
- Low-speed and high-speed technology developed;

Research issues:

- Rotor component improvement;
- Flywheel farm approach;
- High-power applications;
- Longer operation periods;
- Self-discharge limitation.

### 3.9. Super-capacitors energy storage (SCES)

Main assets:

- Highly efficient technology (RTE ~95%);
- Higher power density (800-2,000 W/kg) and energy density than batteries;
- Quick response;

Research issues:

- Dielectric material development;
- Pseudocapacitors;
- Material prizes must severely come down for the current extremely high cost of SCES to decrease as well.

### 3.10. Superconducting magnetic energy storage (SMES)

Main assets:

- Quick deployment time (response time plus ramping up to peak discharge power) and charging time;
- High power rating (up to 100 MW);

Research issues:

- Reduced RTE related to cooling at around -270ºC;
- Development of materials.

### 3.11. Energy storage in substitute natural gas (SNG)

Main assets (see Figure 4) [9], [10]:

- High potential for energy storage and discharge time, even higher than PHES;
- Environmentally friendly SNG ($CH_4$) can be generated from:
  - Electricity coming from renewable energy in off-peak times, by electrolysis ($H_2 + CO_2$);
  - “Wet” biomass for anaerobic fermentation (biogas to SNG);
  - “Dry” biomass for thermochemical gasification (biosyngas to SNG);

Research issues:

- Clean coal technology, minimization of $CO_2$ emissions for gasification;
- Turbine technology enhancement (high pressure turbine).

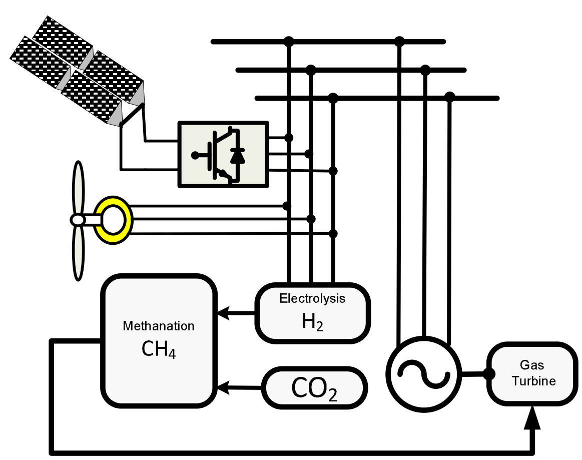


**Figure 4. SNG simplified diagram**

### 3.12. Electric vehicles (EVs)

Main assets:

- G2V and V2G integrated in large-scale would provide very flexible storage and balance the power demand curve;
- EVs work with many battery technologies and fuel cells ($H_2$ produced by electrolysis, and $CH_4$ produced by $H_2$ electrolysis plus $CO_2$);

Research issues:

- Development of Smart Grids;
- Fuel Cell vehicles;
- Price arbitrage incentive regulations must be adequately considered not to induce massive consumption trends.

### 3.13. Promising technologies

Several promising cutting-edge technologies, which have not been discussed previously, are currently being developed:

a) Advanced Na-ion batteries, including Na-halide chemistry
b) New types of Na/S cells (e.g., flat, bipolar, low-temperature, high power).
c) Advanced lead acid batteries.
d) Ultra batteries (a hybrid energy storage that combines VRLA battery with an electrochemical capacitor).
e) Metal air batteries.
f) Mini-CAES, a portable version of CAES.
g) Gravity Power Module (GPMES): a start-up based in California has devised a system that relies on two water-filled shafts, one wider than the other, which are connected at both ends (see Figure 5). Water is pumped down through the smaller shaft to raise a piston in the larger shaft containing a high-weight piston; reversing such a process forces the water to flow back through the pump to generate electricity.

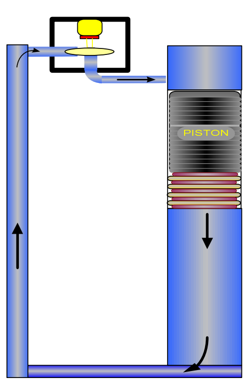


**Figure 5. Gravity Power Module Energy Storage (GPMES) working principle**

h) New flow battery couples, including ion-chrome and zinc-chlorine (ZnCl); but, their suitability for use as utility-scale storage devices is still being studied.
i) Green Power Island concept, in Denmark, which involves building artificial islands with wind turbines and a deep central reservoir.
j) Advanced Rail Energy Storage (ARES) to harness the potential of gravity is under research in Santa Monica, California, this system requires specific topography and delivers more power for the same height to PHES and could achieve more than 85% efficiency. A demonstration system is being built, and should become operational in 2013.
k) CES is a newly developed EES technology (see Figure 6). Off-peak electricity is used to liquefy air or nitrogen, which is then stored in cryogenic tanks. Heat can then be used to superheat the cryogen, boiling the liquid and forming a high pressure gas to drive a turbine to produce electricity. CES is at an early stage of commercialization, with a 500 kW project in the UK [11].
l) Pumped Heat Electricity Storage (PHES) approaches taken by a company based in Cambridge, England. PHES is an energy storage system in the form of heat, which uses argon gas to transfer heat between two vast tanks filled with gravel. Incoming energy drives a heat pump, compressing and heating the argon and creating a temperature differential between two tanks, with one at 500ºC and the other at -160ºC. During periods of high demand, the heat pump runs in reverse as a heat engine, expanding and cooling argon and generating electricity. The system has an overall efficiency of 72-80%, depending on size [12].

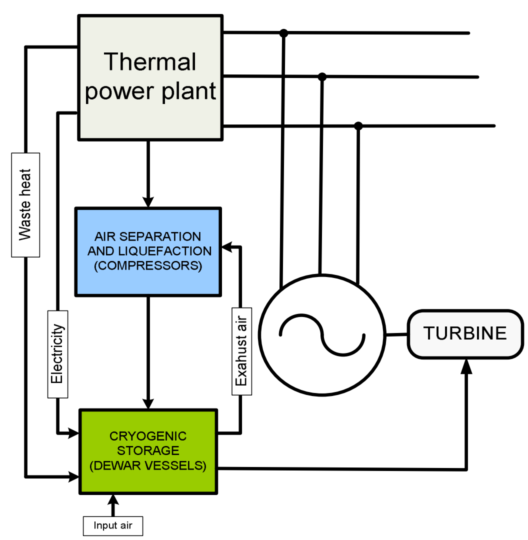


**Figure 6. CES simplified diagram**

## 3.14. Global markets data

Global markets data can be seen in Figure7 and Table 1.

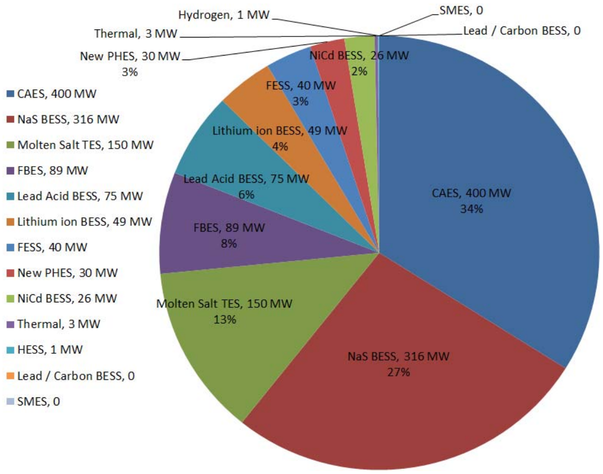


**Figure 7. Global EES Capacity (MW) by Technology (excluding PHES)**

In some cases, different sources provide alternative terms/names for the same meaning and the same application.

This may happen, along with other reasons, due to the fact that they refer to different power systems, European UCTE or others in USA, which have their own definitions for their particular power systems parties, elements, responses, reserves, etc.

**Table 1. Global EES Projects by Region and Installed Capacity**

| | NUMBER OF PROJECTS BY REGION (nº) | | | | | INSTALLED CAPACITY | |
|---|---|---|---|---|---|---|---|
| EES TECHNOLOGIES | North America | Western Europe | Asia Pacific | RoW | Global | Global (MW) | % Total |
| CAES | 1 | 1 | 0 | 0 | 2 | 400 | 33.9% |
| NaS BESS | 8 | 3 | 171 | - | 182 | 316 | 26.8% |
| Molten Salt TES | 0 | 3 | 0 | 0 | 3 | 150 | 12.7% |
| Flow BESS | 11 | 2 | 19 | 1 | 33 | 89 | 7.5% |
| Lead Acid BESS | 19 | 1 | 0 | 0 | 20 | 75 | 6.4% |
| Lithium ion BESS | 6 | 1 | 5 | 2 | 14 | 49 | 4.2% |
| Flywheels FESS | 1 | 0 | 1 | 0 | 2 | 40 | 3.4% |
| New PHES | 0 | 0 | 1 | 0 | 1 | 30 | 2.5% |
| NiCd BESS | 1 | 0 | 0 | 1 | 1 | 26 | 2.2% |
| Thermal TES | 68 | 4 | 9 | 1 | 82 | 3 | 0.3% |
| Hydrogen HESS | 2 | 2 | 0 | 0 | 4 | 1 | 0.1% |
| Lead / Carbon BESS | 0 | 0 | 1 | 0 | 1 | 0 | 0.0% |
| Superconductor | 0 | 0 | 0 | 0 | 0 | 0 | 0.0% |
| TOTAL (excluding PHES) | 117 | 17 | 207 | 5 | 345 | 1,179 | 100.0% |
| PHES (Data of 2013) [24] | - | - | - | - | ~ 350 | 152,000 | Excluded |

## 4. EES applications

There is a wide range of EES applications for power systems, as summarized in Table 2, starting from few seconds-minutes system support to hours-days full load management of grid operations [13].

EES can be integrated at different levels of electrical systems: at generation level, at transmission level, at distribution level, and at customer level. Some concrete ESS application examples, relevant for systems in the Island power supply chain, can be seen in Table 3.

**Table 2. EES Applications [14]-[25]**

| SIZE OF APPLICATION -----> | EES TECHNOLOGIES → vs APPLICATIONS ↓ | | | APPLICATIONS REQUIREMENTS: POWER RATING (MW) | DISCHARGE DURATION (Hrs) | RESPONSE TIME | 1 PUMPED HYDRO-POWER ENERGY STORAGE (PHES) | 2 COMPRESSED AIR ENERGY STORAGE (CAES) | 3 SMALL-SCALE COMPRESED AIR ENERGY STORAGE (SSCAES) | 5 HIDROGEN ENERGY STORAGE SYSTEM (HESS) | 6 CHEMICAL STORAGE / BATTERIES ENERGY STORAGE (BESS) | 7 FLOW BATTERIES ENERGY STORAGE (FBES) | 8 FLYWHEELS ENERGY STORAGE SYSTEM (FESS) | 9 SUPER-CAPACITORS ENERGY STORAGE (SCES) | 10 SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100s MW | ELECTRIC SUPPLY | UTILITY SYSTEM | Provide System Capacity-Resource Adequacy / Electric Supply Capacity / Baseload investment deferral | 1 - 1000 | 4 - 6 | Mins | ● | ● | | | | | | | |
| | | ISO (Independent System Operator) MARKETS | Energy Price Arbitrage / Electric Energy Time-Shift / Renewable Energy Time-Shift / Load Leveling and Peak Shaving | 10 - 1000 | 2 - 10 | Mins | ● | ● | | ● | ● | ● | | | |
| | ANCILLARY SERVICES | | Load following / Provide Spin & Non-Spin Reserves / Electric Supply Reserve Capacity / Conventional Spinning Reserve / Terciary Regulation ( deployment time 15 - 30 minutes) | 10 - 1000 | 2 - 4 | Mins. | ● | ● | ● | ● | ● | ● | | | |
| | | | Provide Spin & Non-Spin Reserves / Electric Supply Reserve Capacity / Fast Response Spinning Reserve / Secondary Regulation (deployment time 2 - 10 minutes) | 10- 1000 | 1 - 2 | < 30 Secs | ● | ● | ● | ● | ● | ● | | | |
| | | | Provide Voltage & Frequency Regulation / Area Regulation / Prinary Regulation (deployment time 15 - 30 seconds) | 1 - 1000 | 15 - 30 Mins | Inmediate | | | | ● | ● | ● | ● | | ● |
| | | | Provide Black-Start and Ramp / Power system Start - Up | 100 - 1000 | 1 - 6 | Secs | ● | ● | | ● | ● | ● | | | |
| 10s MW | RENEWABLES INTEGRATION | UTILITY SYSTEM | Renewable Energy Integration (seasonal output shifting) / Renewable Capacity Firming / Renewables Back - Up | 0.001 - 400 | 2 - 4 | Mins | ● | ● | ● | ● | ● | ● | | | |
| | | | Renewable Energy Integration (daily output shifting) / Renewables Generation Grid Integration (long duration) / Load Leveling | 0.2 - 400 | 1 - 6 | Mins | ● | ● | ● | ● | ● | ● | | | |
| | | | Centralized Renewable Energy Integration (smoothing) / Renewables Generation Grid Integration (short duration) / Fluctuation Supression | 0.2 - 400 | 10 Secs - 15 Mins | Secs - Mins | | ● | ● | ● | ● | ● | ● | ● | ● |
| | GRID SYSTEM | TRANSMISSION | Transmission Congestion Relief / Defer Transmission Investment / Transmission Upgrade Deferral | 0.25 - 100 | 2 - 6 | Mins | ● | ● | ● | ● | ● | ● | | | |
| 100s kW | | DISTRIBUTION | Reduce Outage Frequency-Duration / Electric Service Reliability / Uninterrumpible Power Supply (UPS) | 0.002 - 10 | 4 - 10 | Secs - Mins | | | ● | ● | ● | ● | ● | | |
| | | | Defer Distribution Investment / Distribution Upgrade Deferral | 0.25 - 10 | 2 - 6 | Mins | | | ● | ● | ● | ● | | | |
| | | | Provide Voltage Support Grid Stabilization / Transmission Support / Voltage Control Support | 10 - 100 | > 15 Mins | < 1/4 cycle | ● | | ● | ● | ● | ● | ● | ● | ● |
| 10s kW | END-USER / UTILITY CUSTOMER | END-USER | Improve Power Reliability / Electric Service Reliability / UPS | 0.002 - 10 | 5 Mins - 2 | < 1/4 cycle | | | | ● | ● | ● | ● | ● | |
| | | | Improve Power Quality / Electric Service Power Quality / Transit and end-use ride-through / LVRT / Oscilation Damping | 0.002 - 10 | 10 Secs - 15 Mins | < 1/4 cycle | | | | ● | ● | ● | ● | ● | ● |

On occasions there is a need at generation plants for a black start, which is a process of restoration of a power plant to normal operation without relying on the transmission grid support.

Also, generation bridging support can be provided using EES, until a conventional generator starts up or restarts, so EES has the ability to firm generators load or give a ramping support, picking up fast load variations and allowing a given generator to level its production to the technical limits.

In power distribution systems EES may also find suitable applications counterbalancing contingency effects in order to reduce impacts of the loss of major grid components, as well as in emergency situations after a loss of major grid components. On the customer side, energy management applications of EES systems is another important function, which aims at the reduction of the invoice by securing the continuity of supply at pick hours at accessible price.

However, there are some limiting factors, since most EES technologies are only used for specific applications, and may be completely unsuitable for other applications. Thus, in the next decade R&D effort should be directed towards extending the EES applications range, using a hybrid approach to complement their deficiencies and create a versatile EES system with multifunctional capabilities. Such hybridization would be similar to a well known combination of flywheel storage with battery storage, employed not as a substitute, but as a complement, improving the batteries performance and their life-cycle.

Regarding future development prospects, in the European EES roadmap towards 2030 document, a new multi-functionality hybrid EES system has been proposed, which combines the use of Liquid Hydrogen (LH2) with SMES. The LIQHYSMES approach offers substantial gains with up-scaling both in terms of the efficiency and cost reduction, and thus addressing especially the range of tens to hundreds of MW and GWh [26].

An effort has been made on gathering all the synonyms separating them by "/" in one single application (one cell) in order to clarify the terminology. On top of that, this has enabled us to classify according to the power systems element or shareholder involved and function.

Three main characteristics/requirements have been defined for each application: power rating, discharge duration and response time.

An EES is considered suitable for a certain application if, according to its features, it meets all the corresponding requirements along with other issues such as maturity. Cost-effectiveness has not been taken into account in the previous table, only technical features were considered. Related charts from other sources have been studied. Only EES technologies with enough available data regarding to their application have been included.

The summary of EES technology applications, compiled in Table 3, is for various medium and big size Islands. Moreover, the state-of-the-art of EES technologies, regarding the key features of the most relevant ones, has been summarized in Table 4.

**Table 3. Medium and big size islands' power systems storage applications [27]**

| | LOCATION | | DEMOGRAPHIC FEATURES | | | ELECTRICITY SYSTEM | | | EES | | | START DATE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PROJECT | REGION | POPULATION SERVED | END-USERS | PEAK DEMAND | TYPE | INSTALLED POWER MIX | RENEWABLE PENETRATION | TECHNOLOGY | FEATURES | APPLICATIONS | |
| BIG-size ( > 35- 40 MW ) | Kaheawa Wind Power Project II | Maaleea, Maui Island, Hawaii (USA) | 145,000 (68,000 customers) | Tourist and agricultural Island | 195 MW | Wind / PV / Fossil & Battery Storage | Aprox. 290 MW Fossil, 72 MW Wind and 1.2 MW PV | - | Advanced Lead - Acid Battery | 10 MW, 45 mins. Designed for applications on 21 MW Kaheawa Wind Power Project II | 1) Ramping<br>2) Renewables Energy Time Shift<br>3) Frequency Regulation<br>4) Electric Supply Reserve Capacity - Spinning | 2012 |
| BIG-size ( > 35- 40 MW ) | Kaheawa Wind Power | Maui Island, Hawaii (USA) | 145,000 (68,000 customers) | Tourist and agricultural Island | 195 MW | Wind / PV / Fossil & Battery | Aprox. 290 MW Fossil, 72 MW Wind and 1.2 | - | Advanced Lead - Acid Battery | 1.5 MW, 15 mins. Designed for applications on 30 | 1) Renewables Capacity Firming<br>2) Ramping | July 2009 |
| BIG-size ( > 35- 40 MW ) | Kaua'i Island | Koloa, Hawaii (USA) | ~ 67,000 | Tourist Island | ~ 80 MW | Hydro / PV / Fossil & Battery Storage | 96.5 MW Fossil, 7 MW Hydro and (1.2 + 3) MW PV | 11% | Advanced Lead - Acid Batteries | 1.5 MW, 15 mins. Designed to mitigate the variability of a 3 MW PV array in Koloa substation. | 1) Electric Supply Reserve Capacity - Non-Spinning<br>2) Ramping<br>3) Renewables Capacity Firming | December 2011 |
| MEDIUM - SIZE ( < 35 MW ) | Bonaire Island | Lesser Antilles Archipielago, Caribbean Sea (Netherlands) | 14,500 | Island | 12 MW | Wind / BioDiesel & Battery Storage | 25 MW (14 MW BioDiesel and 11 MW Wind) | 100% | Nickel-based Battery (SMRX Block battery) | 3 MW (2 mins), 640 V, 1,320 Ah (845 kWh) | 1) Back-up for frequency control<br>2) Artificial load<br>3) Power Quality | 2010 |
| MEDIUM - SIZE ( < 35 MW ) | Catalina Island | Channel Islands of California, California. Pacific Ocean (USA) | ~ 4,100 | Tourist Island | 5 MW | - | - | - | Sodium Sulfur Battery | 1 MW. Designed along with the existing diesel generation in order to allow it to work more often a optimal N0x | 1) Electric Energy Time Shift<br>2) Voltage Support<br>3) Electric Supply Capacity<br>4) Grid-Connected Residential (Reliability)<br>5) Electric Supply Reserve Capacity - Spinning | 2011 |

**Table 4. EES technologies' key features [1], [2], [5], [14]-[19]**

| ESS TECHNOLOGIES → DEFINING FEATURES ↓ | | Unit | 1 PUMPED HYDRO-POWER ENERGY STORAGE (PHES) | 2 COMPRESSED AIR ENERGY STORAGE (CAES) | 3 SMALL-SCALE COMPRESED AIR ENERGY STORAGE (SSCAES) | 4 THERMAL ENERGY STORAGE (TES) | 5 HIDROGEN ENERGY STORAGE SYSTEM (HESS) | 6 CHEMICAL STORAGE / BATTERIES ENERGY STORAGE (BESS) | 7 FLOW BATTERIES ENERGY STORAGE (FBES) | 8 FLYWHEELS ENERGY STORAGE SYSTEM (FESS) | 9 SUPER-CAPACITORS ENERGY STORAGE (SCES) | 10 SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COST | INITIAL CAPITAL COST / INVESTMENT PER KW | [$/Kw] | 500 - 4,300 | 425 - 1,250 | 517 & 1,950 - 2,150 | - | 1,100 - 2,600 | - | 1,200 - 2,000 | 300 - 2,200 | 300 | 300 |
| | INITIAL CAPITAL COST / INVESTMENT PER KWh | [$/kWh] | 5 - 430 | 3 - 150 | 50 & 390 - 430 | 3,500 - 7,000 | 2 - 15 | - | 175 - 800 | 170 - 8,800 | 82,000 | 2,000 - 72,000 |
| EFFICIENCY | ROUNDTRIP EFFICIENCY (RTE) | [%] | 65 - 87 | 64 - 80 | 50 - 57 | < 60 | 34 - 42 | 60 - 90 | 60 - 88 | 80 - 95 | 95 | 80 -95 |
| ELECTRICAL CAPACITY | POWER RATING | [MW] | 0.00001 - 4,000 | 20 - 500 | 3 - 100 | 0.1 - 200 | 0.0001 - 50 | 0.0001 - 50 | 0.005 - 25 | 0.1 - 20 | < 0.25 | 0.001 - 100 |
| | ENERGY STORAGE CAPACITY | [MWh] | 0.0005 - 24,000 | 400 - 7,000 | 250 | < 2,000 | 0.00012 - 200 | < 40 | 0.1 - 120 | 0.0052 - 5 | < 3 | < 0.25 |
| | POWER DENSITY | [W/kg] | - | - | - | - | - | - | - | 11.9 | 800 - 2,000 | - |
| | ENERGY MASS DENSITY | [Wh/kg] | 0.5 - 1.5 | 3.2 - 5.5 | - | - | 100 - 1,000 | - | - | 5 - 100 | - | 10 - 75 |
| STORAGE / DISCHARGE BEHAVIOUR | RESPONSE TIME | - | Sec - Min | Sec - Min | Sec - Min | - | < 1/4 cycle | ~ 20 ms | < 1/4 cycle | < 4 ms | < 1/4 cycle | ~ 17 ms |
| | DISCHARGE DURATION | - | 1 hr - Days | 6 Hrs - Days | 1 - 6 hrs | Hrs | Min - Hrs | Min - Hrs | 2 - 20 Hrs | < 1 Hr | Sec - Min | 1 s - 30 min |
| LIFETIME | DISCHARGE CYCLES | [nº] | 20,000 - 50,000 | 10,000 - 30,000 | > 10,000 | - | - | - | 1,000 - 13,000 | 100,000 - 10,000,000 | 10,000 | 10,000 - 100,000 |
| | LIFESPAN / LONGEVITY | [years] | 30 - 50 | 30 - 40 | 30 | - | 2 - 20 | 2 - 16 | 10 - 20 | 20 - 30 | 8 - 40 | 20 - 40 |
| MATURITY | | | Mature | Mature | Demonstration | Mature | Demonstration | - | Commercial | Commercial | Commercial | Mature |
| APPLICATIONS | SHORT TERM [a few seconds or minutes], LONG TERM [minutes or hours] or REAL-LONG TERM [many hours to days] | | Real Long-Term | Real Long-Term | - | Long-Term | Long-Term | Long-Term | - | Short-Term | Short Term | Short-Term |
| | POWER AND/OR ENERGY APPLICATIONS | | POWER & ENERGY | POWER & ENERGY | BRIDGING | POWER & ENERGY | BRIDGING | BRIDGING | BRIDGING | BRIDGING | ENERGY | POWER |

## 5. Conclusion

In the present paper, the need for increasing the EES worldwide capacity has been substantiated by providing the rationale behind the technical and economic benefits, always along with the inherent environmental interest. The main advantages and research issues for leading EES systems have also been analyzed, as well as EES integration data by technology and by region in Figure 7 and Table 1. Furthermore, Table 2 showed a detailed list of specific technical applications classified by function and stakeholders where their corresponding electrical requirements are crossed with the most relevant EES features. It shows whether they meet or not the respective application needs. Table 3 presented a summary of medium and big practical applications of EES systems and their advantages in islands. The state-of-the-art of EES technologies was summarized in Table 4. Several institutional sources like SANDIA, EPRI white paper, IRENA, EERA, CEC (California Energy Commission reports) have been considered to compare similar terminologies applied for EES and the related parameters or technical features, unifying the used terminology.

Finally, it can be stated that the current general research issues related to EES are:

- Design improvement of existing storage systems. Even PHES technology, which is the most mature of all, is involved in design enhancement research.
- Improvement of life expectancy models in terms of cycling capacity. Charge/discharge use is critical in BESS.
- Improvement on storage efficiency evaluation models.
- The influence of different storage options in large-scale wind integration of insular grid systems. EES makes an excellent partner for wind generation, particularly on islands where wind resources are highly available and electrical storage is more essential for power quality and, above all, power system reliability.
- Complete study of interaction and optimization of storage with integrated grid elements and renewable sources.
- Large-scale deployment of bulk storage systems that will require regulator as well as technical progress. MWs grid applications for currently mature technologies for kWs applications.

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