Battery energy storage systems (bess) state of the art

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Summary: This article presents a review of the battery energy storage method or BESS for its acronym in English (Battery Energy Storage System), considering that the era of high capacity storage batteries is approaching and why historically the storage of energy did not appear in the planning or operation of electrical systems. However, this solution is currently setting a global trend for having high levels of efficiency and why it is also being driven by the need to modernize the network in order to increase the use of renewable energies.

Keywords: Batteries, Energy storage systems, Technologies, Efficiency, Renewable energies.

1. Introduction

In a report entitled The Global Market for Grid-Connected Energy Storage Battery Systems, analysts at US consultancy Frost & Sullivan say we are facing a period of “dynamic growth” where commercialization of systems is expected to of storage will skyrocket after 2017. The great ‘boom’ of storage systems is predicted for after 2020, when the fall in their costs will allow the facilities to be amortized in five six years.[one]

Demand for Battery Energy Storage Systems (BESS) is being driven by the need to modernize the grid for the greater use of renewable energy.

Although there are barely 430 MW of BESS operating in the current market, this market is expected to reach between 10 and 12 GW connected to the grid in 2024. This will mean that the market will exceed 460 million dollars (407 million euros) entered in 2014 to about 8,440 million dollars (7,500 million euros) in 2024.

As indicated by various other reports and projects, lithium-ion (Li-ion) technology will continue to dominate the market, "at least for the next 2-3 years," remaining the leading technology in terms of installed power.

In fact, the penetration of renewable sources in the SEP’s networks has increased notably in recent years. However, the power supplied by these energy sources is not as safe and easy to adjust to changes in demand as the power supplied by traditional energy systems. As a consequence, and in order to guarantee the reliability, quality and performance of these systems, energy storage devices are integrated into the networks, simultaneously with these sources.[two]

This document presents the development of battery energy storage systems that propose their use in SEP’s. The characteristic expressions of the same, specific applications and comparative data of the different technologies in technical and economic terms are shown.[one]
2. STATE OF THE ART

Geographically, the US will lead the market for battery energy storage systems (BESS), followed by China, Japan and Germany. With regard to the main companies, NGK Insulators, AES Energy Storage, Sumitomo Electric, LG Chem, Samsung SDI, NEC Energy, BYD, Toshiba, GE and Saft stand out.

Energy storage has the ability to bring flexibility to the grid through a variety of end-use applications, “Its greatest advantages are that it improves the amount of energy that can be distributed, avoids fluctuations in renewable energy and time displacement of electricity, as well as a rapid short-term balance of electricity for secondary markets.”

Despite the bright future that they predict for energy storage systems, they point to a series of obstacles that this emerging market will need to overcome, among which the following stand out:

- High costs
- The low maturity of the technology
- The lack of a clear business model and value proposition
- Limited practical applications that support laboratory efficiency and safety standards
- Inadequate incentives and lack of supportive goals and policies
- Few market consolidations for turnkey solutions
- Low oil and gas prices

"In general, the attractive price, combined with an increase in manufacturing and support policies for the development of renewable energy, will increase the financing capacity of energy storage projects associated with renewable energy."

2.1. Characteristics of storage technologies

There are many techniques for storage, based on practically all forms of energy: mechanical, chemical and thermal.

The storage technologies used present technical and economic criteria, which vary considerably, depending on the specific needs and applications. These technologies can be divided into four categories, depending on the applications:
1. Low power applications in isolated areas, essentially to power transducers and emergency terminals.
2. Medium power applications in isolated areas, individual electrical systems and electrical supply to cities.
3. Network connection application with Peak leveling.
4. Power-quality control applications.

The first two categories are suitable for small-scale systems, where energy could be stored in the form of kinetic energy, chemical energy, compressed air, hydrogen, supercapacitors, and superconductors.

The third and fourth categories are suitable for large-scale systems, where energy could be stored as gravitational energy in hydraulic systems, thermal energy in the form of latent and sensible heat, chemical energy in accumulators and batteries, or compressed air.

2.1.1. Energy storage systems
The different modes of energy storage are set out below, considering the most relevant properties of the different technologies.[5]

A. Flywheel (Flywheels store energy in its kinetic form.)
B. Superconducting Magnetic Energy Storage (SMES), This consists of a large superconducting coil, which is kept at cryogenic temperature by a cooler or cryostat containing helium or liquid nitrogen.
C. Supercapacitors (They are used as storage units in power systems, vehicles, etc.)
D. Compressed Air Energy Storage (CAES). In this technology, the air is compressed and stored in underground tanks, aquifers or cavities. Stored energy is released during peak demand intervals, expanding the air through a turbine.
E. Pumped Hydroelectric Energy Storage (PHES). This technology enables the use of electrical energy in off-peak hours, to pump water from a lower reservoir to another located at a higher altitude.
F. Battery Electric Storage System (BESS), in this case we will develop the topic in greater depth below.

2.2. Battery Energy Storage Systems (BESS)

2.2.1. General characteristics
Reversible electrochemical accumulators, or batteries, are devices that store energy in chemical form inside. Basically, they are made up of a positive pole or cathode, a negative pole or anode, and an electrolyte, which is the substance in which the first two are submerged. The movement and
recombination of the ions and/or molecules that are part of these three elements allows a circulation of direct current to occur when an external circuit connected to the electrodes is closed, which flows through it from the cathode to the anode when the battery discharges, and vice versa when charged.\cite{6}

![Basic Battery Operation](image)

Fig. 2. Basic Battery Operation

There are many types of electric batteries, made of different materials, and in each one the chemical reactions that take place inside are different. In some, such as lead-acid, the electrolyte reacts with the active substances at the poles, thereby altering its composition. In others, such as lithium-ion batteries, the composition of the electrolyte remains unchanged and it only participates by transporting ions from one side to the other. Finally, there are batteries in which only chemical changes take place in the electrolyte, without the plates undergoing any change.

In any case, all batteries share certain common characteristics, which will be detailed below.

![Characteristic curve for a lithium-ion battery model](image)

Fig. 3. Characteristic curve for a lithium-ion battery model

### 2.2.2. Main Types of Batteries

#### 2.2.2.1. Lead-Acid

Lead-acid accumulators are the oldest kind of battery that exists, having been invented in 1859. They are characterized by being capable of providing a high instantaneous current, and have a high power density, due to which they have been used massively in the automotive industry, as a source of energy for the starter motors of gasoline vehicles, among other things
2.2.2.2. Nickel

Nickel-based batteries are another alternative for large-scale energy storage. There are several types, of which the most common is nickel-cadmium (NiCd) batteries, which are a mature technology. In them, a nickel oxide-hydroxide cathode, a metallic cadmium anode, and potassium hydroxide are used as the electrolyte.

2.2.2.3. Ion-Lithium

Lithium-ion batteries are well known for the great success they have had in the portable electronic device market, mainly due to their very high energy density. They are also becoming widely used in electric vehicles, and recently they have also been used as BESS in electrical networks. In particular, in Chile there are already projects in operation that use this type of battery to perform support functions for the Primary Frequency Control (CPF) in the SING.

2.2.2.4. Sodium-Sulfur

Sodium-sulfur (NaS) batteries, despite not being as well known as previous battery types, can be a very good alternative to BESS, and have been commercially available on the market for over ten years.

2.2.2.5. Flow Batteries

This is a newer technology than the previous ones. So-called "flow batteries" differ from conventional batteries in that the chemical elements or compounds that react in them are stored in external tanks, and are only introduced into the device during operation. This implies that the relationship between power and energy in these accumulators is not fixed. On the contrary, while the power is limited by the number of cells used, the energy and capacity of the battery depend on the amount of electrolyte in the tanks. Also, it means that to recharge the battery, you can simply replace the electrolyte.

2.2.2.6. Other Technologies

In addition to those described, there are other types of electrochemical accumulators being developed today that have the potential to become competitive in this market. These have mostly not been used
commercially yet, but several appear to be promising. Here are some of the lines of research that are being followed today:

**Zinc-bromine:** A type of accumulator that has a lot in common with the vanadium redox battery, since it uses tanks to store the electrolyte just like this one. However, part of the active material is also incorporated into the cell itself, which is why it is known as a "hybrid flow battery". Its main advantage is its low cost. In addition, they have a useful life of more than 2,000 cycles with a discharge of 100% of their capacity.

**Metal-air:** They have a very good energy density and have the potential to be very low cost relative to other electrochemical accumulators. However, their life cycles are short, they are not very efficient, and, as their degree of development is low, it is very complex to recharge them.

**Sodium ion:** Similar to sodium-sulfur, with the difference that they can be manufactured on a small scale since they work at room temperature. They are also predicted to become relatively cheap in the future.

**Magnesium-antimony (Liquid Metal Battery):** A type of battery that could have a very low cost, due to the abundance of the elements that compose it. In it, both electrodes and the electrolyte are in a liquid state, and they stratify at different levels due to their difference in density. The negative electrode is made up of magnesium, the positive one of antimony, and the electrolyte is a molten salt. Experimental results in relation to this type of battery indicate that it would have an efficiency of 69%, a high power density and a low self-discharge rate.[7]. However, as in the case of NaS accumulators, maintaining the liquid state of metals requires high operating temperatures.[4]

### 2.2.2.7. Summary table with the characteristics of the main battery technologies

The following table presents a summary with the main characteristics of the most important types of batteries that have been mentioned in this section, and that are currently being marketed worldwide in the form of BESS. The technologies considered are: lithium-ion, lead-acid type VLA (Vented Lead-Acid), lead-acid type VRLA (Valve Regulated Lead-Acid), sodium-sulfur (NaS), nickelcadmium (NiCd) and Vanadium Redox ( VRB).
Table 1: Characteristics of different types of batteries

| TECNOLOGÍA       | TENSION CARACTERÍSTICA | EFICIENCIA (%) | VIDA UTI (select) | TASA DE AUTODESCARGA | DENSIDAD DE ENERGÍA (por volumen) | DENSIDAD DE ENERGÍA (por peso) |
|------------------|------------------------|----------------|-------------------|----------------------|----------------------------------|--------------------------------|
| Ion-Litio        | 3.7 [V] para LiCoO₂; 3.3 [V] para LiFePO₄ | 90             | 3.000 ciclos para 100% DOD; 4.000 para 80% DOD; 20.800 para 30% DOD | 2% mensual | 200-400 [kWh/m³] | 80-160 [Wh/kg] |
| Plomo-Ácidos, Tipo VLA | 2.0 [V]            | 80             | 1.500 ciclos para 100% DOD; 2.000 para 80% DOD; 4.000 para 50% DOD; 6.000 para 30% DOD | 5% mensual | 25 [kWh/m³] | 25 [Wh/kg] |
| Plomo-Ácidos, Tipo VR/LA | 2.0 [V]          | 80             | 750 ciclos para 100% DOD; 2.000 para 80% DOD; 2.000 para 50% DOD; 3.000 para 30% DOD | 4% mensual | 60 [kWh/m³] | 40 [Wh/kg] |
| NiH | 1.2 [V] | 88 | 2.500 ciclos para 100% DOD; 6.500 para 80% DOD; 6.500 para 55% DOD | - | 170 [kWh/m³] | 100 [Wh/kg] |
| NiCd | 1.2 [V] | 70 | 2.000 ciclos para 100% DOD; 3.000 para 80% DOD | 10% mensual | 65 [kWh/m³] | 45 [Wh/kg] |
| VRB | 1.4 [V] | 72 | 5.000 ciclos para 100% DOD; 10.000 para 75% DOD | - [n] | 25 [kWh/m³] | 25 [Wh/kg] |

Notes:
(1). Including PCS losses.
(2). In many cases, particularly with lead-acid batteries, it is not technically feasible for the batteries to discharge to 100% of their capacity, as this could damage the cells.
(3). In addition to the number of charge / discharge cycles that the batteries endure, the life of the BESS may be limited by the useful life of other components, such as the PCS, or the pumps, and ponds for the case of Vanadium Redox batteries.
(4). Self-discharge is nil for applications that do not require a quick response in this type of BESS. However, if this is not the case, it would be of considerable value, as the electrolyte pumps would have to be kept running permanently.

2.2.3. Components of a BESS

Commercial Battery Storage Systems, as already mentioned, are almost always modular, consisting of several elements in addition to the batteries themselves. Some suppliers offer integrated systems in which all these components come inside containers designed to deliver certain power and energy, depending on the customer’s requirements. In other cases, companies that manufacture the different elements work together to develop the system, and the different components can be physically separated into different blocks. The topology to be used varies from case to case, depending, among other things, on the battery technology used, the function that the BESS is intended to fulfill, and the physical and electrical characteristics of the place where the battery is carried out, installation.

The essential components found in any BESS are batteries, DC-AC converters, BMS [7], a master controller, and a system of protections and relays. In addition, a power transformer is almost always needed to make the interconnection with the main power bus of the place where the system is being installed. Additionally, the BESS could require a Thermal Management System, harmonic filters, DC-DC converters type "chopper", power boards for auxiliary services, communication systems with distant
external elements (SCADA type), and other elements according to the particular requirements of each project.

Below is an example of two possible connection topologies between these elements that can be used for this type of system:

Fig. 6. BESS with all its elements in the same container

In this figure, all the elements, except the power transformer, are physically inside the same container. The common bus of the electrochemical cells is connected directly to the input of the inverter, which in turn is connected to the transformer. The main controller and BMS are also housed in the container, and since the inverter and batteries need a certain temperature to operate properly, a Thermal Management System is used to keep it at proper levels.[8]

Fig. 7. BESS with Batteries and PCS physically separated

In the second case, instead, the inverter is in a separate container from the electrochemical accumulators, and, additionally, a DC-DC converter is used to change the direct voltage level before the input to the inverter. The set of converter, controller and filters in this case is usually called PCS (“Power Control System”).

The basic functions of the mentioned BESS components are briefly explained below.

- **Batteries**

They are the most important element of the BESS, and are often the most expensive component of it. They consist of a series of cells that are connected in series and parallel arrangements. By connecting them in series, the continuous voltage with which the BESS operates is achieved, which varies according to the type of technology and characteristics of the project. Among the factors that determine the final voltage
level chosen, it is worth mentioning that, on the one hand, it seeks to reduce the ohmic losses in the battery (which is achieved, for a given power level, by increasing the voltage and decreasing the current), and, on the other hand, the maximum admissible levels must be respected for safety reasons. Typically, DC voltages are used in the common bus of the cells between 400 [V] and 1,200 [V].

- **Converter**

The DC-AC converter is the element that allows the interconnection of the batteries, which operate in direct current, with the electrical network, which operates in alternating current, allowing there to be power flows from one to the other, in both directions. They consist of power electronic circuits, which work from valves made up of semiconductor devices, such as IGBTs or IGCTs.[9]

- **BMS**

BMS ("Battery Management System") are an essential component of BESS. They are electronic equipment that performs monitoring, equalization and protection functions of electrochemical cells, as well as communication with other systems. They are responsible for measuring certain parameters of the cells, such as their voltage and temperature, estimating their state of charge and health, and sending certain orders that allow them to be loaded or unloaded properly.[7]

- **Controller**

This essential element of the system is in charge of ensuring the correct functioning of the BESS. It has multiple functionalities. For example, it sends modulating signals to the inverter valves that allow a control of active and reactive power to and from the batteries.[7]

**2.2.4. Protection System**

It includes the safety switches, measuring transformers and relays that the system incorporates to be able to act appropriately in case of failure. You generally have switches on both the DC and AC side of the inverter. The relays are in charge of comparing magnitudes such as currents, voltages and angles in the main bars, measured by current and potential transformers, and based on that they decide if the system is in a fault state, in which case a Open signal to switches or fuses.

**2.2.5. Transformer**

In most cases, it is necessary to incorporate a transformer to increase the voltage at the inverter output and to interconnect with the electrical grid. Generally, a transformer is used for this to bring the voltage from low to medium voltage (typical values in Chile are 12 [kV], 13.2 [kV] and 23 [kV]), similar to the transformers used in Distribution.[8]

There are few applications where it is necessary to raise to higher voltages. Only in some very large projects in which the BESS causes the power delivered from a plant or substation to increase considerably at certain times it becomes necessary to additionally incorporate a power transformer for high voltage.

The price of transformers, as in the case of inverters, is linked to their nominal power. Furthermore, in some cases the use of multiple inverters in parallel implies that multiple transformers in parallel, or three-winding transformers, must also be used for technical reasons.
2.2.6. Temperature Management System

As already mentioned, it is extremely important to keep the temperature of the batteries at optimal levels, because the useful life and the total charge that they are capable of delivering are negatively affected if the temperature goes too far from these values. Inverters also need to operate within a certain temperature range, although these are located far from batteries at times.

Most battery technologies operate well at temperatures close to room temperature, but high currents tend to cause them to heat up. For this reason, it is necessary to cool them using air conditioning systems, and, in some cases, more complex systems based on the circulation of some cooling liquid. Sodium-sulfur batteries, however, unlike most, only operate at high temperatures, so in this case the Temperature Management System is in charge of heating them.

2.2.7. Additional Civil Works

Finally, a battery energy storage project often requires a significant investment in infrastructure in many cases. While many commercially available BESSs are built into containers that can be installed outdoors, in other cases, and particularly with batteries that tend to take up more space, such as lead-acid and nickel-cadmium batteries, storage may be required. Construction of special buildings to house the equipment. Within this item the wiring, conduits, and grounding of the structures are also considered. [11-12]

3. CONCLUSIONS

This document presents the most relevant properties of energy storage technologies currently being developed in the design of power systems. In this sense, the parameters that characterize the behavior of the different technologies are exposed, in order to properly use them.

Considering permanent low-power applications, where the key phenomenon is possible self-discharge, lithium-ion batteries are presented as the most successful technology.

In small electrical systems, of a few kWh, located in isolated areas and based on renewable resources, the most relevant characteristic for opting for one technology or another is autonomy, so the lead battery is the most appropriate.

REFERENCES

[1] «The era of high-capacity storage batteries is coming | Electricity Sector | Professionals in Electrical Engineering », 2016.
[2] «Energy Storage Technologies for Electric Applications ». [Online]. Available at: http://www.sc.ehu.es/sbweb/energias-renovables/temas/almacenamiento_1/almacenamiento_1.html. [Accessed: Dec 20, 2016].
[3] "Smart Energy Consulting: Batteries connected to the grid", Smart Energy Consulting, Sep 18, 2015. 
[4] El Pedro Estévez, Maider Varela, «Energy storage systems for renewable energies», 2016.
[5] "Energy Storage Technologies for Electric Applications". 2016.
[6] ABM Shawkat Ali, Smart Grids: Opportunities, Developments, and Trends. 2013.
[7] MT Lawder et al., "Battery energy storage system (BESS) and battery management system (BMS) for grid-scale applications", Proc. IEEE, vol. 102, no 6, pp. 1014-1030, 2014.
[8] S. Chouhan, D. Tiwari, H. Inan, S. Khushalani-solanki, and A. Feliachi, "DER Optimization to Determine Optimum BESS Charge / Discharge Schedule using Linear Programming", 2016.

[9] D. Rodríguez, R. Gómez, and A. Campos, «Battery management systems (BMS) and their importance for battery storage systems (BESS)», Tecnura, pp. 51-56, 2015.

[10] "Keys to understanding energy storage". [Online]. Available at: http://www.revistaei.cl/reportajes/claves-para-entender-el-almacenamiento-de-energia/[Accessed: Dec 21, 2016].

[11] M. Arunkumar, M. Kannan, G. Murali, Experimental studies on engine performance and emission characteristics using castor biodiesel as fuel in CI engine, Renewable Energy, Volume 131, 2019, Pages 737-744, ISSN 0960-1481

[12] Loganathan N., Arvin Tony A., Malini T., Gobhinath S. (2020) Comparison of Renewable Energy Generation in an Electrical Network with Energy Storage System. In: Lecture Notes in Electrical Engineering, vol 626. Springer, https://doi.org/10.1007/978-981-15-2256-7_3