SURVEY OF ELECTRIC ENERGY STORAGE SYSTEM AND TECHNOLOGIES

Ahmed Alseed
Zawia University
a.alssid@zu.edu.ly

Abstract

Electricity demand is increasing rapidly, because of large increases in population and economic growth. Hence electricity generation authorities have struggled to provide a reliable electricity supply to consumers but facing many obstacles to meeting the needed demand. Therefore, energy storage is becoming a necessary option in integrating renewable resources improving power quality; aiding the shift towards distributed energy, and helping the network operate under more stringent environmental requirements as well as lowering associated costs. In this paper, a review of electric energy storage systems and technologies has been explored focusing on gride-scale electro-chemical types (battery energy storage), namely Lead-Acid (LA); Nickel-Cadmium (NiCad); Sodium-Sulphur (NaS), in terms of their application and advantages and disadvantages as well as their future prospective.

Keywords: battery storage system, demand, energy, costs

I. Introduction

Traditional electricity networks are supplied by large, centralized, and highly predictable generating stations. An inherent characteristic of such networks is that supply must meet demand at all times. Typically matching supply with demand on a network requires backup sources of power, such as an open-cycle gas turbine, or by a storage system. As the electricity sector is undergoing a lot of change, energy storage is becoming a realistic option for restructuring the electricity market; integrating renewable resources; improving power quality; aiding the shift towards distributed energy; and helping the network to operate under more stringent environmental requirements. In addition, energy storage could improve the existing generation and transmission infrastructures whilst also preventing expensive upgrades. Power fluctuations from renewable resources will prevent their large-scale penetration into the network [ ]. However, energy storage devices can manage these irregularities and thus aid the amalgamation of renewable technologies. In relation to conventional power production, energy storage devices can improve overall power quality and reliability, which is becoming more important for modern commercial applications. Finally, energy storage devices can reduce emissions by aiding the transition to newer, cleaner technologies such as renewable resources and the hydrogen economy. A few difficulties have disadvantaged the commercialization of energy storage devices including a lack of experience since more prototype projects should be set up to raise consumer confidence, and inconclusive benefits. Consumers do not understand what exactly the benefits of energy storage are in terms of savings and power quality, and high capital costs. This is clearly an issue when the first two disadvantages are considered: responsibility for the cost. Developers view storage as ‘grid infrastructure' whereas the Transmission System Operator (TSO) views it as part of the renewable energy plant.

II. Energy Storage Device Parameters

In general, there are many parameters that describe energy storage device parameters regardless of its types. Some of these parameters are defined as follows:

- ***Power capacity*** is the maximum instantaneous output that an energy storage device can provide, usually measured in kilowatts (kW) or megawatts (MW).
- ***Energy storage capacity*** is the amount of electrical energy the device can store, usually measured in kilowatt-hours (kWh) or megawatt-hours (MWh).
- ***Efficiency*** indicates the quantity of electricity that can be recovered as a percentage of the electricity used to charge the device.
- ***Response time*** is the length of time it takes the storage device to start releasing power.
- ***Round-trip efficiency*** indicates the quantity of electricity which can be recovered as a percentage of the electricity used to charge and discharge the device.

There are some extra parameters specific to the battery storage devices and these include:

- ***Charge-to-discharge ratio*** is the ratio of the time it takes to charge the device relative to the time it takes to discharge the device. For example, if a device takes 5 times longer to charge than to discharge, it has a charge-to-discharge ratio of 5:1.
- ***Depth of discharge*** (**DoD**) is the percentage of the battery capacity that is discharged during a cycle.
- ***Memory effect***. If certain batteries are never fully discharged, they 'remember' this and lose some of their capacity.

BES system is becoming a very prominent technology because it has many promising features such as modular system, quiet operation, minimum, quick installation, environmental manipulation, non-polluting parts, Possibility to achieve a wide range of technical features, relatively fast response time, high power and energy density, High efficiency

III. Energy Storage System Components

Every energy storage system consists of three primary components: storage medium, power conversion sub-system, and balance of the system.

1. Storage medium

The storage medium is the 'energy reservoir' that keeps the potential energy within a storage device. Storage media range from mechanical, pumped-hydroelectric energy storage (PHES), chemical, battery energy storage (BES) and electrical, superconducting magnetic energy storage (SMES) potential energy.

2. Power conversion sub-system

It is necessary to convert from alternating current (AC) to direct current (DC) and vice versa, for all storage devices except mechanical storage devices, e.g. PHES and CAES [1]. Consequently, a power conversion subsystem is required that acts as a rectifier while the energy device is charged (AC to DC) and as an inverter when the device is discharged (DC to AC). The power conversion subsystem also conditions the power during conversion to ensure that no damage is done to the storage device.

The customization of the power conversion subsystem for individual storage systems has been identified as one of the primary sources of improvement for energy storage facilities, as each storage device operates differently during charging, standing and discharging [1]. The power conversion subsystem usually costs from 33 to 50% of the entire storage facility. Development of power conversion subsystems has been slow due to the limited growth in distributed energy resources e.g. small-scale power generation technologies ranging from 3 to 10,000 kW [1].

3. Supporting facilities

This includes all additional works and ancillary components required to:

- house the equipment
- control the environment of the storage facility
- provide the electrical connection between the power conversion subsystem and the power grid It is the most variable cost component within an energy storage device due to the various requirements for each facility. The supporting facilities “typically include electrical interconnections, surge protection devices, a support rack for the storage medium, the facility shelter, and environmental control systems” [1]. The supporting facilities may also include foundations, roadways, access, security equipment, electrical switchgear, and metering equipment. Development activities including all paperwork, design, planning, safety, training and their costs are often included here.

IV. Battery Energy Storage

Battery Energy Storage Systems (BESS) can be defined as rechargeable batteries that could store energy from dissimilar sources and release it while needed. Battery Energy Storage comprises of a single or more than one battery and could be applied to balance the electric network, deliver backup power, and enhance network stability.

Total installed grid-scale battery storage capacity stood at close to 16 GW at the end of 2021, most of which was added over the course of the previous]. five years [7]

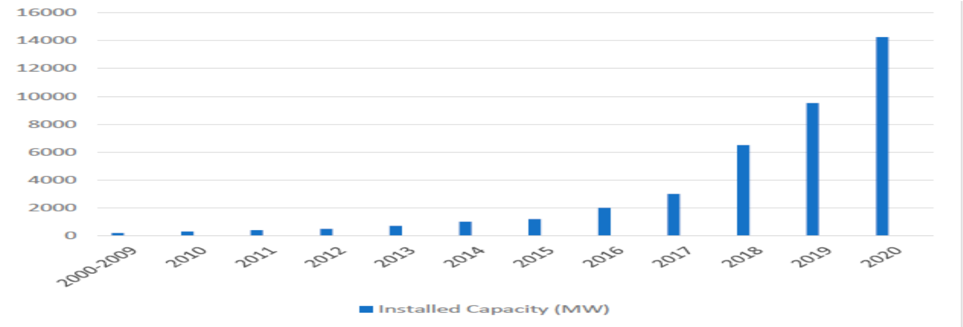

Fig. 1 Global electrochemical energy storage market size by cumulative installed capacity [7]

There are various ESS solutions available today, but lithium-ion batteries are currently the technology of choice due to their cost-effectiveness and high efficiency. Based on the technique of operation, there are a variety of energy storage systems such as batteries, flywheels, pumped hydro, supercapacitors, and compressed air energy storage. Thus, choosing a storage device that could make the required function effectively is a primary step, as most storage devices are expensive. In this paper, we will focus on the chemical type of energy storage technology, specifically battery energy storage technology (BES).

There are three important types of large-scale BES. These are: Lead-Acid (LA); Nickel-Cadmium (NiCd); Sodium-Sulphur (NaS**).** These types operate in the same way as conventional batteries, except on a large scale, i.e., two electrodes are immersed in an electrolyte, which allows a chemical reaction to take place so current can be produced when required.

1. LA battery

This is the most common energy storage device in use at present. Its success is due to its maturity, relatively low cost, long lifespan, fast response, and low self-discharge rate. These batteries can be used for both short-term applications (seconds) and long-term applications (up to 8 h). There are two types of LA batteries; flooded lead-acid (FLA) and valve-regulated lead-acid (VRLA). FLA batteries are made up of two electrodes that are constructed using lead plates which are immersed in a mixture of water (65%) and sulphuric acid (35%). VRLA batteries have the same operating principle as FLA batteries, but they are sealed with a pressure-regulating valve. This eliminates air from entering the cells and also prevents venting of the hydrogen. VRLA batteries have lower maintenance costs, weigh less and occupy less space. However, these advantages are coupled with higher initial costs and shorter lifetime. Both the power and energy capacities of LA batteries are based on the size and geometry of the electrodes. The power capacity can be increased by increasing the surface area for each electrode, which means greater quantities of thinner electrode plates in the battery. However, to increase the storage capacity of the battery, the mass of each electrode must be increased, which means fewer and thicker plates. Consequently, a compromise must be met for each application. LA batteries can respond within milliseconds at full power. The average DC–DC efficiency of a LA battery is 75–85% during normal operation, with a life of approximately 5 years or 250–1000 charge/discharge cycles, depending on the depth of discharge [1].

Applications of LA battery

FLA batteries have two primary applications [1]:

1. Starting and ignition, short bursts of strong power e.g. car engine batteries
2. Deep cycle, low steady power over a long time.

VRLA batteries are very popular for backup power, standby power supplies in telecommunications and also for UPS systems

Cost of LA battery

Costs for LA battery technology have been stated as \$200/kW to \$300/kW [1], but also in the region of \$580/kW [1].

Disadvantages of LA battery

LA batteries are extremely sensitive to their environments. The typical operating temperature for a LA battery is roughly 27°C, but a change in temperature of 5°C or more can cut the life of the battery by 50%. However, if the depth of discharge exceeds this, the cycle life of the battery will also be reduced. Finally, a typical charge to-discharge ratio of a LA battery is 5:1. At faster rates of charge, the cell will be damaged.

Future of LA battery

Due to the low cost and maturity of the LA battery, it will probably always be useful for specific applications. The international *Advanced Lead-Acid Battery Consortium* is also developing a technique to significantly improve storage capacity and also recharge the battery in only a few minutes, instead of the current hours [1].

However, the requirements of new large-scale storage devices would significantly limit the life of a LA battery. Consequently, a lot of research has been directed towards other areas. Therefore, it is unlikely that LA batteries will be competing for future large-scale multi-MW applications.

2. NiCd battery

A NiCd battery is made up of a positive with nickel oxy-hydroxide as the active material and a negative electrode composed of metallic cadmium. These are separated by a nylon divider. The electrolyte, which undergoes no significant changes during operation, is aqueous potassium hydroxide. During discharge, the nickel oxy-hydroxide combines with water and produces nickel hydroxide and a hydroxide ion. Cadmium hydroxide is produced at the negative electrode. To charge the battery the process can be reversed. However, during charging, oxygen can be produced at the positive electrode and hydrogen can be produced at the negative electrode. As a result some venting and water addition is required, but much less than required for a LA battery.

There are two NiCd battery designs: vented and sealed. Sealed NiCd batteries are the common, everyday rechargeable batteries used in a remote control, lamp, etc. No gases are released from these batteries, unless a fault occurs. Vented NiCd batteries have the same operating principles as sealed ones, but gas is released if overcharging or rapid discharging occurs. The oxygen and hydrogen are released through a low pressure release valve making the battery safer, lighter, more economical, and more robust than sealed NiCd batteries.

The DC–DC efficiency of a NiCd battery is 60–70% during normal operation although the life of these batteries is relatively high at 10–15 years, depending on the application. NiCd batteries with a pocket-plate design have a life of 1000 charge/discharge cycles, and batteries with sintered electrodes have a life of 3500 charge/discharge cycles. NiCd batteries can respond at full power within milliseconds. At small depth of discharge rates (approximately 10%) NiCd batteries have a much longer life cycle (50,000 cycles) than other batteries such as LA batteries. They can also operate over a much wider temperature range than LA batteries, with some able to withstand occasional temperatures as high as 50°C.

Applications of NiCd battery

Sealed NiCd batteries are used commonly in commercial electronic products such as a remote control, where light weight, portability, and rechargeable power are important. Vented NiCd batteries are used in aircraft and diesel engine starters, where large energy per weight and volume are critical [1]. NiCd batteries are ideal for protecting power quality against voltage sags and providing standby power in harsh conditions. Recently, NiCd batteries have become popular as storage for solar generation because they can withstand high temperatures.

Cost of NiCd battery

NiCd batteries cost more than LA batteries at $600/kW [1]. However, despite the slightly higher initial cost, NiCd batteries have much lower maintenance costs due to their environmental tolerance.

Disadvantages of NiCd battery

Like LA batteries, the life of NiCd batteries can be greatly reduced due to the depth of discharge and rapid charge/discharge cycles. However, NiCd batteries suffer from ‘memory’ effects and also lose more energy during self-discharge standby than LA batteries, with an estimated 2–5% of their charge lost per month at room temperature in comparison to 1% per month for LA batteries [1]. Also, the environmental effects of NiCd batteries have become a widespread concern in recent years as cadmium is a toxic material. This creates a number of problems for disposing of the batteries.

Future of NiCd battery

It is predicted that NiCd batteries will remain popular within their current market areas, but like LA batteries, it is unlikely that they will be used for future large-scale projects. Although just to note, a 40 MW NiCd storage facility was constructed in Alaska; comprising of 13,760 cells at a cost of $35M [1]. The cold temperatures experienced were the primary driving force behind the use NiCd as a storage medium. NiCd will probably remain more expensive than LA batteries, but they do provide better power delivery. However, due to the toxicity of cadmium, standards and regulations for NiCd batteries will continue to rise.

3. NaS battery

NaS batteries have three times the energy density of LA, a longer life span, and lower maintenance. These batteries are made up of a cylindrical electrochemical cell that contains a molten-sodium negative electrode and a molten-sulphur positive electrode. The electrolyte used is solid β -alumina. During discharging, sodium ions pass through the β -alumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulphide. During charging, the reaction is reversed so that the sodium polysulphide decomposes, and the sodium ions are converted to sodium at the positive electrode. In order to keep the sodium and sulphur molten in the battery, and to obtain adequate conductivity in the electrolyte, they are housed in a thermally insulated enclosure that must keep it above 270°C, usually at 320–340°C. A typical NaS module is 50 kW at 360 kWh or 50 kW at 430 kWh. The average round-trip energy efficiency of a NaS battery is 86% to 89% [1]. The cycle life is much better than for LA or NiCd batteries. At 100% depth of discharge, the NaS batteries can last approximately 2500 cycles. As with other batteries, this increases as the depth of discharge decreases; at 90% depth of discharge the unit can cycle 4500 times and at 20% depth of discharge 40,000 times [1].

One of the greatest characteristics of NaS batteries is its ability to provide power in a single, continuous discharge or else in shorter larger pulses (up to five times higher than the continuous rating). It is also capable of pulsing in the middle of a long-term discharge. This flexibility makes it very advantageous for numerous applications such as energy management and power quality. Currently, NaS batteries cost $810/kW, but it is only a recently commercialized product. This cost is likely to be reduced as production increases, with some predicting reductions upwards of 33% [1]. The major disadvantage of NaS batteries is retaining the device at elevated temperatures above 270°C. It is not only energy consuming, but it also brings with it problems such as thermal

management and safety regulations. Also, due to harsh chemical environments, the insulators can be a problem as they slowly become conducting and self-discharge the battery.
A 6 MW, 8 h unit has been built by *Tokyo Electric Power Company* (TEPCO) and *NGK Insulators, Ltd.* (NGK), in Tokyo, Japan with an overall plant efficiency of 75% and is thus far proving to be a success. The materials required to create a NaS battery are inexpensive and abundant, and 99% of the battery is recyclable. The NaS battery has the potential to be used on a MW scale by combining modules. Combining this with its functionality to mitigate power disturbances, NaS batteries could be a viable option for smoothing the output from wind turbines into the power grid [1]. *American Electric Power* is planning to incorporate a 6 MW NaS battery with a wind farm for a 2-year demonstration. The size of the wind farm has yet to be announced but the results from this will be vital for the future of the NaS battery.

V. Related research

Battery Energy storage system is used as a backup system due to power outages, which may be caused by extreme weather events, asset failure, natural disasters, power surges, acute accidents, and even operational errors by the workforce.
Over the years various studies have been conducted on the topic of energy storage systems (ESSs). These studies considered power system resilience to curtail power outages. Resilience is the ability of a system to survive, sustain, and rapidly recover from extreme and unexpected disruptions.

In a study in the USA [2] on the best configurations to enhance the power resilience of residential electricity supply, three configurations of power system supply (PSS) were studied and these are (1)- Electrical Grid (EG) + Battery Energy Storage (BES),(2)- (EG) + (BES) + Natural Gas Power Generator (NGPG) and (3)- (EG) + (BES) + Photovoltaic (PV).

EG + PV + BES configuration would enhance the power resilience of residential users better than the other two PSS configurations. Besides, it is also observed that the identified resilient PSS configuration is cost-effective and environmentally efficient.

In [3] a large-scale power system transient stability improvement by incorporating a large size Battery Energy Storage System (BESS) was investigated,
The results showed that system's transient stability

Performance can be improved by the positioning of a BESS in the system. The BSS not only provides improved transient stability but also maintains the increased power transfer ability of the system. Furthermore, the influence of faults on the DC side of a BESS to the connected AC network is investigated. the obtained results of [3] showed that the DC faults in a BESS need to be considered very carefully to avoid its negative impacts on the connected AC system; particularly for a large amount BESS which could have a noticeable effect on the connected power system.

In a further study [4]. a mixed integer linear programming model for optimal battery energy storage system operation in distribution networks was proposed. The proposed model considers several parts of the battery energy storage system including the battery pack, inverter, and transformer in addition to linear modeling of the reactive power and apparent power flow limit. Furthermore, a linear power flow model is applied to evaluate voltage magnitudes and power losses with high accuracy. The proposed model was applied to the IEEE 33 bus test case. The results of the simulations showed that the proposed modeling and scheduling of the BESS will enhance its benefits so that, the total daily operation cost is decreased by 3.7 percent with respect to the case in which the BESS reactive power contribution in not considered.

In addition, the voltage index of the buses was approximately improved by 30 % which results in a smoother voltage profile. Furthermore, total daily active and reactive power losses of the network showed a 23.90 and 22.50 % reduction, respectively. The study concluded that the achieved extra benefits owing to considering the BESS reactive power can help to compensate high investment costs of the storage devices. Results also prove the accuracy and efficiency of the proposed model. In conclusion the results demonstrate that considering reactive capability of the batteries offers new benefits including voltage profile improvement, decreasing reactive power flow in the network, reducing network losses, and releasing network and substation capacity.

Research also considered the role the BESS can play in multi-microgrid optimization. The study in [5], concentrated on energy management with BESS optimization to reduce distribution, and generation costs. This work focuses on the energy consumption schedule as well as the optimization of BESS capacity in the multi-microgrid. In particular, the optimization is formulated by using a non-cooperative and cooperative programming approach.

The study illustrated that the non-cooperative and cooperative optimization approaches achieve approximately equivalent overall results, e.g. sensibly flattening the demand curve and reducing the fluctuation of interactive power between a public power system and multi-microgrid. It also showed that the daily cost of each microgrid in a cooperative mechanism is slightly lower than the cost in a non-cooperative mechanism. Moreover, the islanded operation of multi-microgrid was also analyzed considering BESS as the individual energy source. The results explained that optimal BESS capacity could meet the operation requirements of multi-grid from the aspect of the longest islanded operating time.

The authors in [6], considered the requirements of BES in a microgrid system, which include technical, environmental, and economical. They claimed that combining renewable energy sources with BES in a microgrid system will improve the reliability and stability of energy sources. They think that the high cost of batteries is the main hurdle when designing an energy storage system for a microgrid. They suggested that one of the methods to reduce the use of batteries by employing a hybrid energy storage system in which a combination of two or more energy storages is considered in a microgrid system. In order to design a storage system in an economical way, many parameters have to be considered such as, depth of discharge, battery lifetime and degradation, temperature, charge/discharge current, and battery placement in an optimization algorithm. Research on optimization and forecasting algorithms is rapidly evolving as more and more types of algorithms are introduced in literature studies. Moreover, at the end of the battery life cycle, the disposal of batteries has become problematic in recent years. The heavy toxic chemical and materials have a negative impact on the environment. To reduce this impact, recycling and the second use of batteries have been implemented by battery manufacturers. However, further policies and enforcement should be introduced to support safe battery disposal and recycling. In addition, novel materials used in the batteries should also consider the recyclability of the materials as part of the research.

A review of BESS with its past overview and evaluation for renewable integration is considered in [8]. Among the different battery storage systems, the most mature battery technology at this moment is he lead–acid battery [9,10].

VI. Conclusion

A review of electric energy storage systems and technologies focusing on gride-scale electro-chemical types (battery energy storage) has been presented in this paper, The review was done in terms of their benefits, disadvantages, application, and future trends The fast increase in power generation from renewable energy sources (RES) makes the use of large-scale and cost-effective ESS a requirement for the reliability of the power system.

It is very hard to forecast which category of energy storage system would dictate the market but at present, electrochemical energy storage systems dictate the market share. Including electrochemical energy storage systems, Li-ion batteries are considered a more competitive option for grid-scale energy storage applications as they have a high energy density, are lightweight, and have high efficiency.

As a concluding remark, ESS technologies have great capability to enhance the operation of electric power grids and to support growth in renewable electricity generation. Energy storage features, when appropriately scheduled, can assure firm power during peak loading conditions

References

1. Martin J. Leahy, David Connolly & Denis N. Buckley, “The Charles Parsons Initiative”, University of Limerick, Ireland.
2. Nallapaneni Manoj Kumar , Aritra Ghosh,* and Shauhrat S. Chopra “Power Resilience Enhancement of a Residential Electricity User Using Photovoltaics and a Battery Energy Storage System under Uncertainty Conditions” Journals, Energies, Volume 13, Issue 16 , 2020.
3. Ujjwal Datta, Akhtar Kalam, Juan Shi, “Battery Energy Storage System for Transient Frequency Stability Enhancement of a Large-Scale Power System”, Australasian Universities Power Engineering Conference (AUPEC) At: Melbourne, Australia , 2018
4. Hasan Mehrjerdi , Reza Hemmati, “Modeling and optimal scheduling of battery energy storage systems in electric power distribution networks”, Journal of Cleaner Production 234 (2019) 810-821, Elsevier Ltd.
5. Xiaofeng Liu, Bingtuan Gao , Zhenyu Zhu, Yi Tang,” Non-cooperative and cooperative optimization of battery energy storage system for energy management in multi-microgrid”, Journal, IET Generation, Transmission & Distribution, 2018.
6. M. Sufyan, N. A. Rahim , M. M. Aman, C. K. Tan, and S. R. S. Raihan, “Sizing and applications of battery energy storage technologies in smart grid system: A review”, Journal of Renewable Sustainable Energy **11**, 014105 (2019);
7. Energy Storage Industry White Paper 2021 (Summary Paper). Available online: www.en.cnesa.org
8. Wali, S.B.; Hannan, M.A.; Reza, M.S.; Ker, P.J.; Begum, R.A.; Rahman, M.S.A.; Mansor, M. Battery storage systems integrated renewable energy sources: A biblio metric analysis towards future directions. J. Energy Storage 2021, 35, 102296.
9. Gur, T.M. Review of electrical energy storage technologies, materials and systems: Challenges and prospects for large-scale grid storage. Energy Environ. Sci. 2018, 11, 2696.
10. Krishan, O.; Suhag, S. An updated review of energy storage systems: Classification and applications in distributed generation power systems incorporating renewable energy resources. Int. J. Energy Res. 2019, 43, 6171–6210