A Review on Battery Technologies for Electrical Energy Storage

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Abstract

Energy management provides the framework for optimised system operation. Energy storage system smoothens the stochastic nature of renewable energy, allows for increased access to renewable energy in remote areas, increase the reliability of micro-grids, plays a major role in the development of hybrid vehicles and serves as energy conservation system in green buildings. The need for increased access to reliable and sustainable energy in developing countries requires more deployment of energy storage technologies, particular, battery technologies. This study provides a review of the technical characteristics and costs comparison of various battery technologies. A single battery technology may not meet all the specification of a system and a wrong application will reduce the potentially derivable value. Hence, a knowledge of technical characteristic of each battery technology is important toward technology adoption.

1. Introduction

Energy storage (ES) system has been identified as an inevitable element for the diversification of primary sources of energy (USA DOE, 2013). The intermittent nature of renewable energy (RE) sources in which the profile of energy generated deviate from the demand profile, can be minimised by implementing ES system (Kousksou et al., 2014). The deviation in demand profile, although follows a predictable pattern, is impossible to forecast with precision as the changes could be instantaneous, minute-to-minutes, hourly, diurnal and seasonal (Almen and Falk, 2013). ES systems bridge the link between variable generation capability of RE sources and the highly volatile grid demand profiles (Notton et al., 2011). The integration of ES systems into a power network, increase the overall efficiency of RE sources over the network, reduce associated cost and emission caused by the use of primary fuel for baseload and peaking plants, and ensure energy supply security, however, it adds to the degree of complexity of the system (Notton et al., 2011). Four major challenges that still pose a threat to the integration of ES system into exiting power grid are; cost competitiveness to other energy system, validated reliability and safety of some technologies, environmental concerns and policies, and industry acceptance (USA DOE, 2013). While other challenges can be addressed by technology advancement and policy frame work, cost competitiveness to other energy systems is still a limitation to the deployment of ES system. Current ES systems are based either solely on or a combination of the following principles of storage; chemical, electrical, mechanical and thermal (Eckroad, 2002). Identifying the most suitable ES system for all applications is complex, as no single storage system can simultaneously provide the least capital and operating cost with high efficiency, as well as extended life time, high power and energy density (Kondoh et al., 2000). Therefore, the right ES system will compromise combination of technologies to match application, power and energy demand while still been economical.

The penetration of renewable energy in developing countries especially for off-grid applications has seen to the increase the battery technologies, operating on electrochemical energy storage principle. About 2 GW of energy storage has been installed in developing countries and it is expected to reach 80 GW by 2025 as presented in Figure 1 (Eller and Gauntlett, 2017). The report highlights the role of battery energy storage technologies. Gloria et al. (2017) highlighted the role of battery in a 100% renewable energy grid in Cape Verde and emphasise its importance. Due to the continued growth in deployment of this technology option, this paper present a review of the battery technologies, compare their characteristics and provide a cost update of different battery technologies.

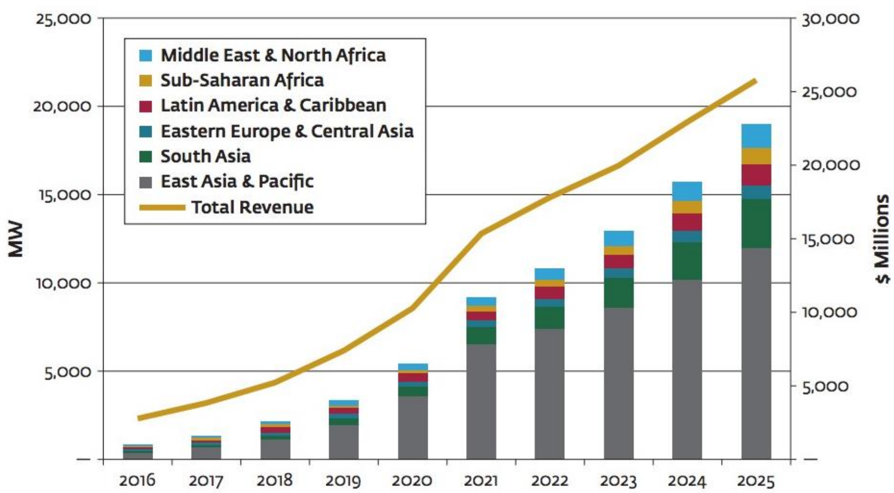

Figure 1 Projected annual stationary ES deployments, power capacity and revenue

2. Classification of Energy Storage Technologies

There are various classification systems for ES technologies as shown in Figure 2. ES technologies are mostly classified by the specific energy and power available for a load as well as the charge/discharge duration (Gunawardane, 2015; Krivik and Baca, 2013; Kularatna, 2015a). Das (2013), classified ES technologies based on scale, characteristics, functional grid services provided, operational mode and demand response. Kousksou et al. (2014), classified ES technologies based on their application; thermal or electrical. The application approach considered the source energy input and output from the ES technologies. Ibrahim et al. (2008), classified ES technologies based on application and storage duration. Power application classified low power and medium power applications as small scale system while peak levelling and power quality control applications were categorised as a large-scale system. Storage duration considered long term and short term storage. Lund et al. (2015), classified ES technologies based on the storage capacity and power capacity. Technologies with higher storage capacity can respond to a longer fluctuation while a higher power capacity can respond to a higher magnitude of fluctuation. SBC (2013), classified ES technologies based on their underlying physical and chemical properties. This classification method is based on the fundamental charging and discharging principles. Chauhan and Saini (2014) and Ibrahim and Ilinca (2013), classified ES technologies based on time frame, form of storage and function of storage. The time frame classification is based on the storage duration and considered short term, medium and long term. Function classification considered ES technologies with small energy content but high power ratings, which are suitable for power quality management, reliability and uninterrupted power supply; and ES technologies designed for energy management. This classification considered the technical performance of the ES technologies. The form classification considered the state at which energy was stored within the storage medium. Within the form classification, chemical ES; electrical ES; mechanical ES; and thermal ES were considered. Storage technologies and application also find classification depending on the duration of their discharge time. Discharge within 30 minutes is classified as power application while above 30 minutes are classified as for energy application (Battke et al., 2013). Based on various classification framework, the battery technologies ES systems described below are based on their physical and chemical properties, as this classification provides a broad view to their charging and discharging principles as well as the state at which energy is stored.

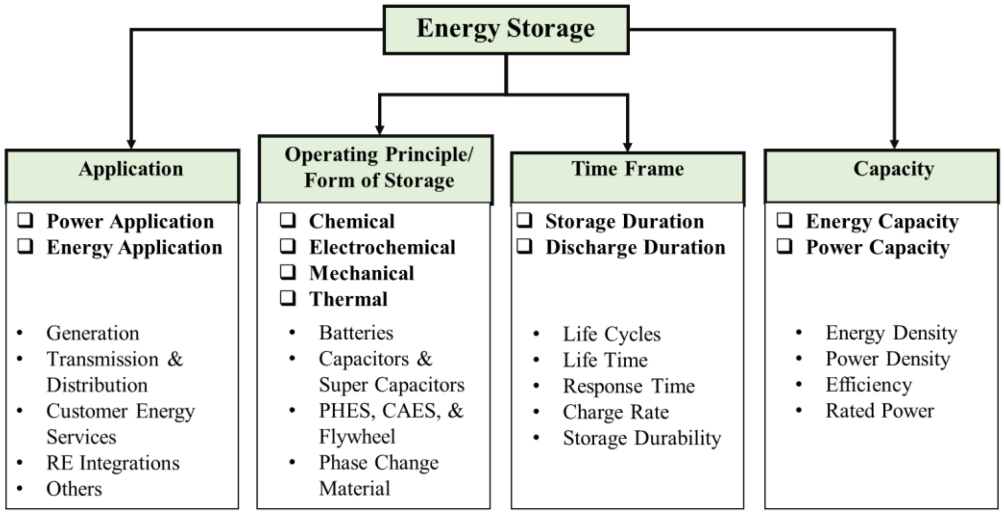

Figure 2 Classification of ES technologies

3. Electrochemical Energy Storage

Batteries are the profound type of electrochemical ES. The general working principle of a battery is the free transfer of electrons between electrodes caused by the oxidation-reduction reverse reaction taking place within the cells of the battery when a load is connected to the electrodes (Díaz-González et al., 2012; Krivik and Baca, 2013). Energy is stored in electrochemical form when an electrode plate is placed in an electrolyte which facilitates the transfer of ions (Schoenung, 2001). The stored energy is a function of the active components that the electrolyte can accommodate (Schoenung, 2001). The surface area of electrode and cell resistance determine the power rating of the battery (Schoenung, 2001). The arrangement of the cells could be in series, parallel or combined depending on the output voltage and energy capacity of the cells. The array of possible chemicals and materials used as electrode and electrolytes creates a wide variety of battery technologies fulfilling different task (Battke et al., 2013). Batteries generally represent high energy density and low power density ES technologies (Hall and Bain, 2008). Batteries are modular, they can be adapted to different site conditions and located at different points across the grid.

3.1 Conventional Batteries

Conventional batteries are primary batteries; they are non-rechargeable and disposed of after stored energy has been exhausted; and secondary batteries, which are rechargeable and can be used over the life cycle of the battery. Primary batteries are generally cheaper, with low discharge rate and higher energy density than secondary batteries (Kousksou et al., 2014). However, they not suitable for bulk ES (Kousksou et al., 2014). Conventional batteries are mainly used for short-term storage purposes as they all possess varying degree of self-discharge losses (Krivik and Baca, 2013). Their response time is about 20 ms (Chauhan and Saini, 2014). When integrated within RE, they are good for power quality management, short-term fluctuation reduction, spinning reserve application and transmission deferral. There are various types of batteries with different merit and demerits.

3.1.1 Lead-acid (PbA) Battery

PbA is a matured technology and accounts for more than 60% of installed secondary batteries (Krivik and Baca, 2013). The main components are electrodes, separating materials, electrolyte, containing vessel, ventilator and some other components as depicted in Figure 3-1A (Krivik and Baca, 2013). They have the least cost per energy capacity, but also have low energy density, poor cold temperature performance and short cycle life (Beaudin et al., 2015). The lifetime varies significantly depending on the application, depth of discharge and number of cycles (University of California, 2011). They are highly reliable and efficiency ranges between 70-90% (Kousksou et al., 2014). Static PbA batteries are not suitable for large-scale applications due to high capital cost and construction difficulties (Mahlia et al., 2014). Flow PbA batteries have been used to overcome challenges of balancing power consumption and generation problems which are associated with static PbA batteries (Mahlia et al., 2014). Valve regulated (VRLA) and carbon PbA batteries are the two advancing PbA batteries for future applications with higher life cycles while other additives such as selenium, and antimony are also being explored to improve performance (Jaiswal and Chalasani, 2015; Mahlia et al., 2014). Conventional PbA batteries do have difficulties to provide frequent power cycles because they are often in a partial state of charge (SOC) which accelerate their failure due to sulphation (Díaz-González et al., 2012; Kousksou et al., 2014). However, new ultra PbA batteries that eliminate the sulphation process and leverages on advanced PbA battery and asymmetric capacitor technologies now provides longer battery life at consistent power cycles (Mahlia et al., 2014). When connected to the grid, they are suitable for power quality, spinning reserve and uninterrupted power supply.

3.1.2 Nickel-Cadmium (Ni-Cd) Battery

Ni-Cd belongs to a group of batteries with a nickel based positive electrode, metallic cadmium negative electrode and an alkaline solution as an electrolyte as shown in Figure 3-1B (Krivik and Baca, 2013). They have higher energy density, quick recharge abilities and cycle lifetime greater than 3500 cycles though highly dependent on the depth of discharge (DoD) and low maintenance requirement compared to lead acid (Díaz-González et al., 2012; Kularatna, 2015b). They are environmental threat due to the presence of cadmium, low cell voltage, high self-discharge rate and are not economical to operate especially with wind and solar energy due to problems caused by memory effect of the battery and capital cost that are 10 times more than the cost of PbA batteries (Díaz-González et al., 2012; Kousksou et al., 2014; Kularatna, 2015b). The environmental pollutant cadmium has been replaced with a non-toxic alloy yielding nickel metal hydride (Ni-MH) which have 25-30% higher energy density but with high self-discharge rate (Krivik and Baca, 2013; Lund et al., 2015; University of California, 2011).

3.1.3 Lithium ion (Li-ion) Battery

Li-ion is the most used and versatile portable battery in the market with less environmental effect. Installed capacity is estimated to reach 35 GWh as of 2015 (EPRI, 2010). They are made-up of metal oxide cathode, a carbon based anode, dissolved lithium salt as an electrolyte and micro-porous sheet separator as shown in Figure 3-1C (Krivik and Baca, 2013). The energy density and cell voltage are almost twice and thrice that of nickel based battery respectively (Kularatna, 2015b). Therefore, fewer cells are required for a given demand with high efficiency and life cycles. It has low self-discharge rate not exceeding 5% per month with life cycle exceeding 1500 cycles, however, it deteriorates faster at high temperatures and not suitable for use at high DoD (Kousksou et al., 2014). Due to its poor performance at high DoD, it is not suitable for a back-up application (Díaz-González et al., 2012). It possesses fast charge and discharges capabilities with less than 200 ms response time to attain 90% rated capacity when responding to a load (Díaz-González et al., 2012). High capital cost is required for large scale applications as well as safety circuitry features to avoid over-charge and over-discharge, hence not yet a matured technology for a grid-scale application (Battke et al., 2013; Kularatna, 2015b). It expected that its application on a grid scale level will become economical in the future due to improved manufacturing processes with new materials. When used as a storage device in a power grid, it functions best as a frequency regulator (Beaudin et al., 2015). The TCC ranges between $400-5000/kW (Inage, 2009).

3.1.4 Sodium-sulphur (NaS) Battery

NaS is a high-temperature battery operating between 300-400 °C which are usually designed in a tubular manner (Dufo-Lopez et al., 2008; Krivik and Baca, 2013). The high temperature allows for increased reactivity as the electrodes and the products of the electrochemical reaction are all in a liquid state (Díaz-González et al., 2012). Sodium, the negative electrode material, and sulphur the positive electrode material are readily available in nature and are considerably cheaper. Ceramic based material, beta-alumina, are often used as electrolyte due to the difficulty of finding suitable aqueous electrolyte (Krivik and Baca, 2013). Sodium-sulphur cell batteries have a high specific energy density in the range of 151-170 kWh/m^3 due to sodium high reduction potential, low atomic weight and efficiency greater than 85% (Kousksou et al., 2014; Krivik and Baca, 2013). Also, due to the availability of construction materials and environmental friendliness with near 99% base material recyclability, it is deemed the most economical battery for energy management within a variable RE source (Dufo-Lopez et al., 2008). However, the system requires high level protection as pure sodium is hazardous, it explodes when in contact with air (Mahlia et al., 2014). Also, it corrodes insulator under a harsh environmental condition, hence increase the rate of self-discharge (Mahlia et al., 2014). Sodium nickel chloride ($NaNiCl_2$) otherwise called ZEBRA, has been developed as an improvement on the short comings of NaS battery (Mahlia et al., 2014). ZEBRA gives about 2500 cycles at 90% DoD with millisecond response time and an approximately 6 hrs discharge duration making it suitable for power regulations on micro-grid (Akhil et al., 2015; Kousksou et al., 2014). High TCC, high-temperature requirement and high self-discharge rate are the demerits of NaS (Kousksou et al., 2014). Figure 3-1C is a section view of the sodium sulphur battery (Kousksou et al., 2014).

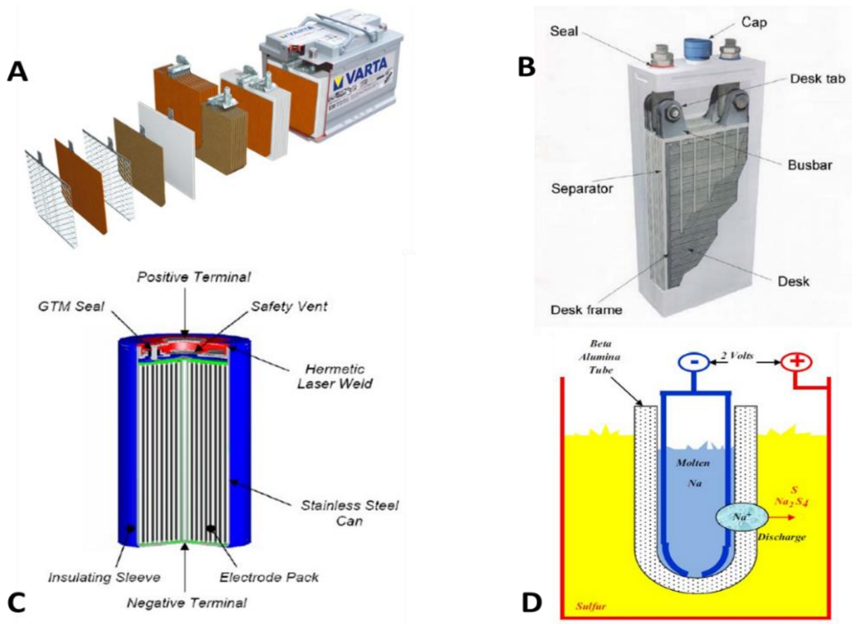

Figure 3-1 Conventional batteries: A: PbA; B: Ni-Cd; C: Li-ion; D: NaS

3.2 Flow Batteries

Flow batteries, also called redox flow batteries, have their principle of operation in the oxidation and reduction reaction of the electrolyte stored in an external separate vessel as shown in Figure 3-2 (Díaz-González et al., 2012; Kousksou et al., 2014). Flow batteries can be fully discharged without any side effect to the components (Díaz-González et al., 2012; Kousksou et al., 2014). The power capacity is independent of the depth of discharge, but rather determined by the area of the electrode, while the energy capacity is a function of the volume of electrolyte (Zakeri and Syri, 2015). Due to the independence of the power and energy capacity, system flexibility and scale-up options are available by increasing the volume or concentration of the electrolyte to increase power capacity (Battke et al., 2013; Krivik and Baca, 2013). They have low self-discharge rate, long life with low maintenance cost and long storage duration (Díaz-González et al., 2012; Kousksou et al., 2014). When integrated into a RE source for power generation, they are used for following load and power quality regulation due to their ultra-fast response time, and pulse capability (Kularatna, 2015b). Available batteries on this working principles have their chemistries to include vanadium, iron-chrome, polysulphide-bromide, zinc bromide, iron-chromium and redox flow batteries (Battke et al., 2013; Beaudin et al., 2015). The life cycle emission and cost estimate for flow batteries are lower compared to conventional batteries (Zakeri and Syri, 2015).

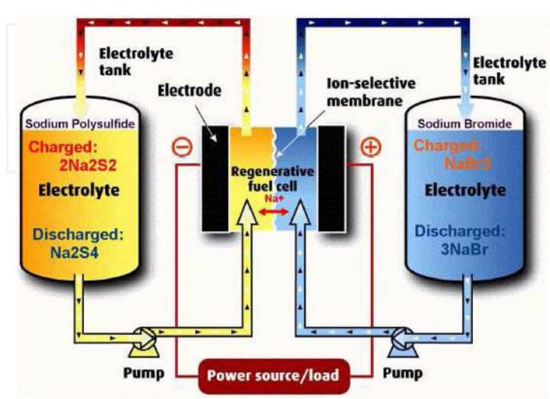

Figure 3-2 Illustration of a flow cell battery

3.3 Comparison of battery technologies

Battery technologies for energy storage can be compared both on technical terms and economic terms. Discharge duration is one technical characteristic that determines of a technology is suitable for power or energy applications. Figure 3 shows NaS, PbA and the flow batteries are suitable for energy application due to long discharge duration capability while Li-ion is suitable for power application. Aside discharge duration, the efficiency of storage technology as well as life impacts on the cost-effectiveness of the technology. The round-trip efficiency of ES system is the ratio of the released energy by the storage to the energy supplied to it. For ESS to be competitive, effective and cost efficient, it must have an overall high efficiency. Figure 4 compares the storage life and efficiency of the battery technologies. the round-trip efficiency ranges between 72% ZnBr to 92% for Li-ion battery. The storage life is highly dependent on the usage, environmental operating conditions, charge-discharge pattern and the type of load the batteries are subjected to.

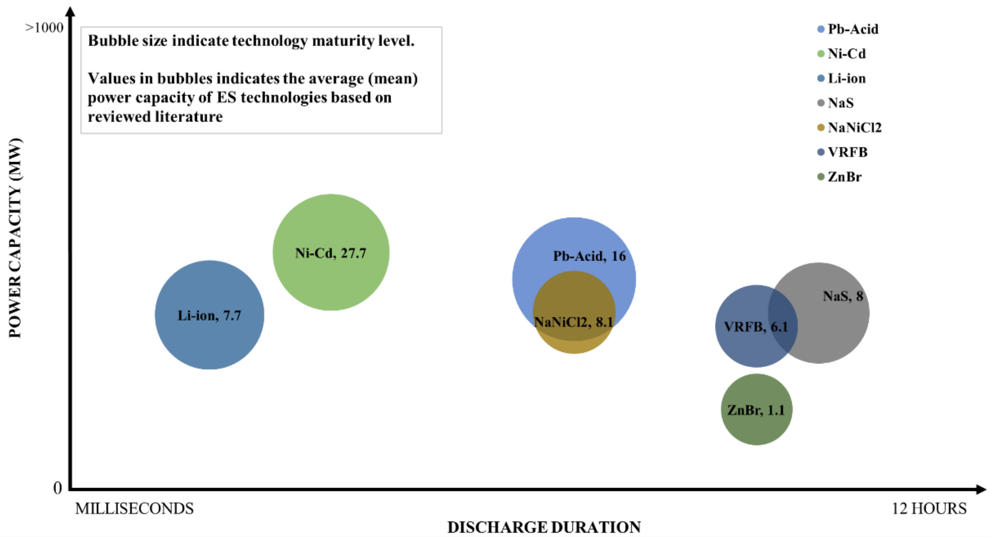

Figure 3 Comparison of battery technologies based on maturity and discharge duration

Figure 4 Combo chart of storage life and efficiency

Energy density and power density is a technical characteristic for comparison of technologies. It is the amount of energy and rated power that is released by the storage system per unit volume or mass respectively. These two parameters describe the size of the system and the needed space to house it. A related term is the foot print which describes the space requirement for installation of the ES system. Figure 5 compares these characteristics.

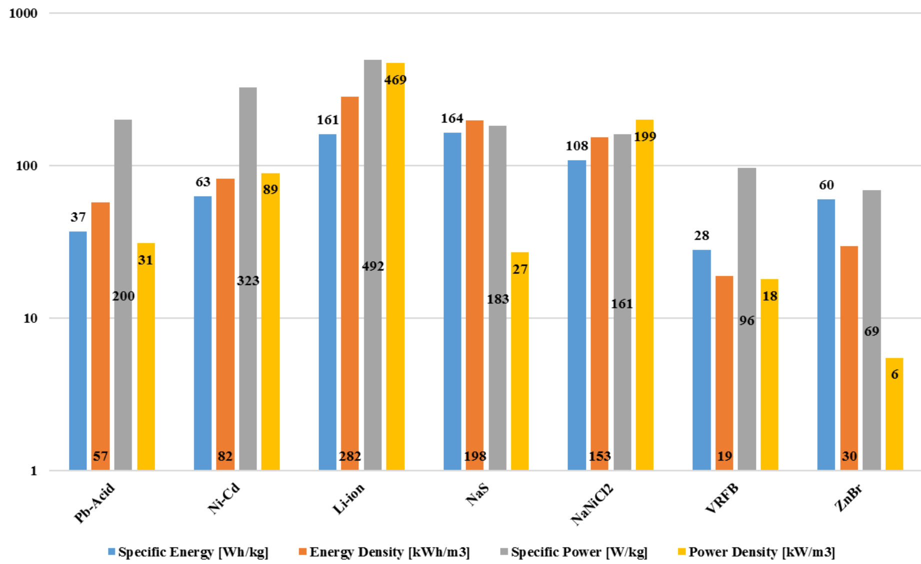

Figure 5 energy and power density of battery technologies

3.4 Cost Comparison

Economic consideration is a key factor towards decision making. Though high capital cost is still a barrier towards the full adoption of energy storage generally, however, reports have highlighted the potential saving implementing battery storage can offer. Utility scale flow battery can offer an annual fuel savings of 1,680 L/kW, lead-acid battery 1,920 L/kW and Li-ion 2,040 L/kW (Eller and Gauntlett, 2017). Table 1 present cost range of battery technologies. The cost of implanting battery technologies differ based on technology application, the location of installation, manufacturer preference and other policy related cost. Recent reports indicated a steady decline in capital cost for battery technologies. a 37.5% price reduction was reported for flow batteries between 2014 and 2016, 31.5% reduction for advanced PbA and 46% reduction for Li-ion batteries (Eller and Gauntlett, 2017).

Table 1 Cost elements of battery technologies

	TCC (Power) [$/kW]	TCC (Energy) [$/kWh]	PCS [$/kW]	Storage [$/kWh]	BOP [$/kW]	Fixed O&M [$/kW-yr]	Var. O&M [$/kWh]	Replacement Cost [$/kW] & (year)
Pb-Acid	400-6,331	110-2,445	143-796	103-953	48-171	1.5-27.44	0.00017-0.0125	56-1,385 (8)
Ni-Cd	662-4,706	234-2,639	161-370	635-1,833	126-128	4.5-34.1	-	538-772
Li-ion	175-5,517	194-4,690	217-654	232-1,405	53-109	2.25-22.21	0.00045-0.0076	210-611 (5)
Na-S	325-3,667	159-1,099	193-973	203-691	50-128	0.64-65.89	0.00033-0.02	124-498 (8)
Zn-Br	200-6,179	117-1,984	170-670	200-596	58-74	3.6-50.26	0.00034-0.004	108-257 (15)
VRFB	675-9,048	57-3,750	225-900	226-772	33-89	3.83-25.74	0.0001-0.00315	125-772 (8)
NaNiCl2	234-5,334	480-1,500	377-718	412-970	-	3.17-8.1	0.00043-0.0024	120-1,287 (8)

4. Conclusion

In this study, a technical and cost review of battery energy storage technologies has been presented. The future growth in the deployment rate of battery technologies will be driven by improved system efficiency with a decline in investment capital cost, increasing penetration of renewable energy and the need for energy access in remote and off-grid locations. ES is an important system integrator for the penetration of renewable energy, especially those with high intermittency, in developing countries.

Acknowledgements

The authors wish to acknowledge the University of Johannesburg for providing grants for this research work.

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