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Comparative Analysis of Battery Storage Technologies for Residential Photovoltaic Solar Energy Installations

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Abstract

The study concerns a comparative analysis of battery storage technologies used for photovoltaic solar energy installations used in residential applications. Battery storage is needed because of the intermittent nature of photovoltaic solar energy generation and also because of the need to store up excess energy generated in periods of high demand or for sales to the National Grid System. The study consists of three parts; namely: (a) to undertake a comprehensive review of current battery storage technologies. (b) To investigate the performance of the main battery storage technologies that is commercially available (efficiency, energy density, power density, self-discharge per day and power rating); (c). Undertake comparison of battery energy storage technologies. From the findings, it shows that the Lithium-Ion Battery technology is the most reliable and most widely used technology for residential applications. It has the best performance characteristics (efficiency, energy density, power density, moderate self-discharge and power rating) however, lithium-ion batteries are still relatively expensive among others. Due to these features the Lithium-Ion Battery technology stands a total chance of dominating the Battery technology market for residential and automotive applications. Also shows from the findings, the performing reliability of the Lithium-ion battery by using the battery application requirements and the dangers in operating at a not required specification. More recommendations were made in areas of challenges faced by the battery storage technologies in order to make improvement.

Keywords*: Battery storage Technologies, Efficiency, Energy density, Moderate self-discharge photovoltaic solar energy, Power density, Power rating*

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Background to the Study

Energy plays the most vital role in the economic growth, progress, and development, as well as poverty eradication and security of any nation. Uninterrupted energy supply is a vital issue for all countries today. Future economic growth crucially depends on the long-term availability of energy from sources that are affordable, accessible, and environmentally friendly. Security, climate change, and public health are closely interrelated with energy (Ramchandra and Boucar 2011). Energy is an important factor in all the sectors of any country's economy. Renewable energy has become a very important field or area of study for the past notable years because of the declining fossil fuel reserves and concerns about global warming. Energy produced from sustainable (renewable) sources of energy like the photovoltaic (PV) solar energy installations used in residential applications that has exhibited momentous development around the world, could hardly provide quick response to consumer demand as a result of the fluctuating nature of the technology as it lacks the ability to make available uninterrupted supply which can effortlessly be adjusted to meet the needs of consumers. However, it can be more reliable if supported by energy storage technologies and the inverter that converts the DC to AC. Batteries for the purpose of storage are key component of any self-reliant renewable energy system like the solar that generates its energy from the sun without been connected to a national grid. The energy in form of electrochemical generated by photovoltaic solar system is stored using the battery. Battery banks serve as a back-up source of energy at night when photovoltaic solar system may not be able to generate as expected to meet the needs of the consumer (Ohwofasa, Umar and Adegbola, 2020).

The Photovoltaic device basic operating principle is to convert solar irradiation into electricity which can be stored using battery storage technologies (Sambo, Zarma, Ugwuoke, Dioha and Ganda, 2012). Technologies for the storage of energy are essential elements of the cutting-edge electrical power systems, both for renewable (sustainable) and conventional power networks applications (Chen, Cong, Yang, Tan, Li and Ding, 2009).

Battery storage technologies are reliable means to reduce or even eliminate the gap between the demand and supply of electricity by the conventional and the renewable energy generation sources. As at present, the storage systems engage in stationary applications like the pumped hydro, compressed-air, superconducting magnetic, capacitors and super-capacitors, fly wheel, pumped heat and battery technologies (Akinyele and Rayudu, 2014). Battery technologies can be regarded as part of the auspicious storage systems for stationary applications, as a result of their maturity and the easy way of designing and installing it compared to other storage technologies (Leadbetter and Swan, 2012, IEEE, 2007). The modern electrical power systems are mounted with quite a lot of challenges which has attracted the attention and intensive efforts of energy system researchers, developers and experts in the field of practice (Daniel, Belikov, and Levron, 2017). Chen et al 2009 pointed out some of the challenges in the area of the system voltage stability and frequency, problems of power quality such as voltage drop and distortion, the output of intermittent renewable energy, bidirectional power flow, energy control, energy demand at peak period, energy supply reliability, integration of renewable energy-based microgrids and large-scale wind power etc. Energy storage system plays an important role in addressing some of the problems mentioned. It is now of interest in this current study of battery storage technologies for residential photovoltaic solar energy installations with the aim to form a significant background by describing the some of the most used different types of battery technologies and their applications, and reviewing some of the existing studies in the literature in order to provide solutions to the mentioned challenges. This will serve as help to identify the milestones reached and the possible research gap. Figure 1 shows the images of photovoltaic solar energy installations connected alongside with the batteries and inverter for residential applications.

Fig. 1: Photovoltaic solar energy installations connected alongside with the batteries and inverter for residential applications (Ohwofasa, 2018).

Statement of the Problem

With ever increasing energy costs, the developed and developing countries households are increasingly looking to use renewable energy technologies such as photovoltaic solar energy systems for generating their own energy. Due to the intermittent nature of photovoltaic solar energy power generation, these household installations require the use of battery storage and inverter system to meet their power demands and in some cases to make them fully energy sufficient and grid independent (Talla*et al.*, 2015). However, the question to ask now is, there are batteries but which one is more durable and reliable? The little or no knowledge about battery storage system brings difficulty about understanding the disadvantages and advantages of diverse technologies for battery storage and decision on which battery technology for storage which is most appropriate for any applications (Inglesi- Lotz, 2015). In achieving this, undertaking a study of battery storages technologies used for photovoltaic solar energy installations in residential applications is needed to be done to know which battery storage system most reliable and suitable for any application.

Research Aim, Objectives

The main purpose of the study was to undertake a comparative analysis of battery storages technologies used for photovoltaic solar energy installations in residential applications. The study will precisely determine the following:

1. To undertake a comprehensive review of current battery storage technologies.
2. To investigate the performance of the main battery storage technologies that is commercially available (efficiency, energy density, power density, self-discharge per day and power rating).
3. Undertake comparison of battery energy storage technologies.

Methodology

This is a literature based conceptual paper. A three main phase's methodology was adopted shown in fig 2 and explained with a means of achieving the required result. The authors reviewed literature on battery storages technologies used for photovoltaic solar energy installations in residential applications that are commercially available with a comparative analysis in view of providing necessary recommendation for the technology that is best suitable and reliable.

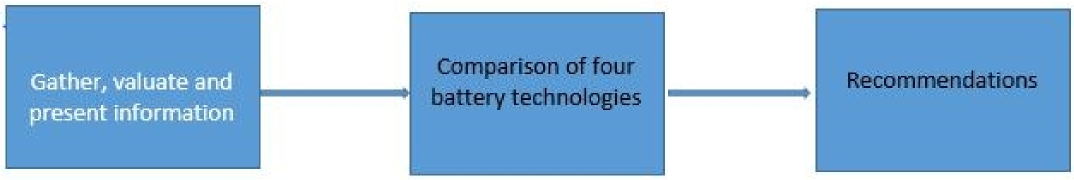


Fig 2: Graphic demonstration of the research workflow

Common battery storage technologies for PV installations

Lead-Acid Batteries

The penetration of lead-acid (LA) into the storage system, has made its chemistry a kind of most popular (Linden, 2010) as a result of its affordability and high reliability. Its first development was recorded in 1860 (Huggins and Robert, 2010). The lead serve as the anode material to the lead acid battery and the same time the lead dioxide function as the cathode, with an acid electrolyte. A charged lead-acid batteries electrolyte has sulfuric acid (H_2SO_4) mixed with water (H_2O).

Tetraoxosulphate (IV) acid is among the three dynamic materials which participate in the production as well as storage of electric power within the lead-acid batteries. At the point of discharging the battery by applying load, there is a movement of electrons from the negative Pb plate down to the PbO2 plate as a result of the reaction from the electrochemical redox between the plates of lead and the electrolytes. Fig. 3 shows a typical example of Lead-acid battery with 6 cells with a yield voltage of 12 Volts.

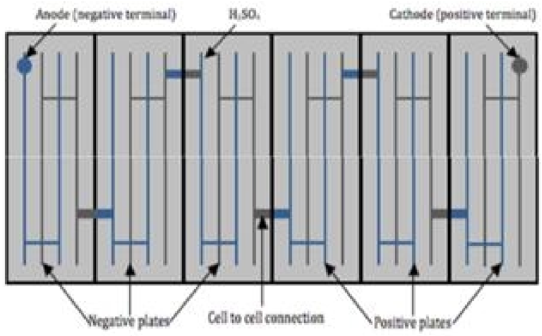


Fig. 3: Six cell Lead acid battery with a voltage output of 12V (Andrews and Jelly, 2013)

Lithium Ion Batteries

Lithium ion batteries (LIB), within their best regular state, comprises of lithium oxides (positive terminal), graphite (negative terminal) as well as an electrolyte of an organic as well as dissolvable lithium salt (Andrews and Jelley 2013). Figure 4 is meant to illustrate the specialized outline of the battery. The battery system of lithium ion as a system for the storage of energy is dependent upon electrochemical discharge/charge reactions occurrence between a negative electrode (anode), composed of materials of carbon, or intercalation compounds and a positive electrode (cathode) which comprises of certain lithiated metal oxides. The cathode lithium atoms forms ions as well as flows by the electrolyte towards the carbon anode as they are combined with electrons and placed between layers of carbon as lithium atoms in the time of the battery charged procedure.

The reversed of the process is discharge. The separated electrodes by porous polymeric materials that allows for ionic as well as electron movement between them, submerged into an electrolyte which is composed of lithium salts (for instance LiPF6) melted in liquids of organic nature.

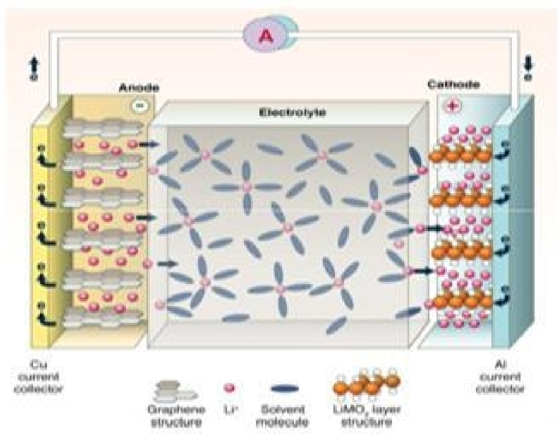


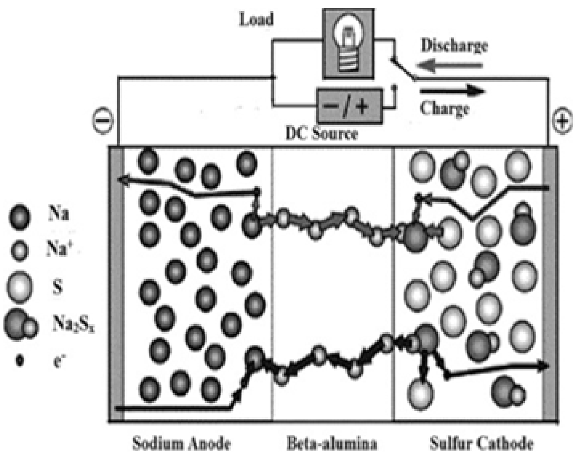
Fig. 4: Schematics drawings explaining the design of LIB (Kamath and Dunn, 2011)

Lithium has low density as well as sizeable typical anode potential bringing about batteries that are of low weight as well as high operational voltage (Andrews and Jelley 2013). Additionally, LIB has no memory impact; low self-charge as well as an outstanding energy to mass proportion amongst other which makes them the primary device for the storage of energy for mobile electronic appliances, for example, cell phones, iPads as well as TVs (Castello, 2012). The properties have been proved as beneficial additionally for vehicles electric footing, power control devices as well as capacity for storage of occasionally accessible renewable energy source thus LIB is ever more typical in these areas of application (Kamath, and Dunn, 2011).

Sodium-Sulfur Batteries

A Sodium-Sulfur (NAS) battery cell utilizes sodium as well as sulfur as the functional materials for the positive as well as negative anodes, correspondingly, as well as sodium-ion conductive β-alumina ceramic functioning as electrolyte. Batteries of NAS work with a high temperature of around 300°C to maintain the materials of the electrodes within a liquid state, therefore decreasing sodium-ion resistance stream by the β-alumina solid electrolyte (Oshima et al., 2004).

Figure 5 demonstrates the principle of operation of a NAS battery cell.



$$2\,Na + x\,S \underset{Charge}{\overset{Discharge}{\rightleftharpoons}} Na_2S_x$$

Fig. 5: NAS battery cell principle of Operation (Oshima et al, 2004)

During Sodium-Sulfur (NAS) battery discharging and charging process, a reversible electrochemical reaction occurs. The Nominal Electromotive Force (EMF) of a functional NAS battery cell is approximately 2 Volts. The moment the cell discharges, anode releases electrons to the exterior circuit as well as sodium ions go through the β-alumina electrolyte and accepted by the positive electrode whereby their reaction with sulfur produces sodium polysulfide. At the point of charging the cell, the process is the other way round, that is, the sodium polysulfide experience decomposition at the terminal that is positive, as well as sodium ions finds their way back to the positive cathode.

Redox Flow Battery

The Redox flow batteries, function as other batteries with conventional principles, the only different is that requires a refill of the electrolytes fluids after discharged. The energy of any Redox flow battery is clearly shown by the volume of the electrolyte and power, in relation to any battery cells electrode area. The Redox flow batteries, irrespective of its commercialisation, still portrays discharge level at a higher and energy densityat a lowerpoint. The process of Redox Flow Batteries (RFB) involves the filling of reverse planes of the electrochemical cell with two disintegrated metal ions fluid electrolytes as dynamic masses. Thus no stage change of these working masses happens. RFB contain different tanks storage isolated by an ion-selective film are the negative and the positive redox species. Coming in contact with the collector, reduction or oxidation reactions is experienced by the Redox-dynamic ions. In many cases, the film permits the non-reaction movement of ions to retain balanced electrolyte as well as electro neutrality (Sarbjit and Munnings 2014). Figure 5 signifies the fundamental standard of RFB with the plan to upgrade understanding the functional appearance of the battery.

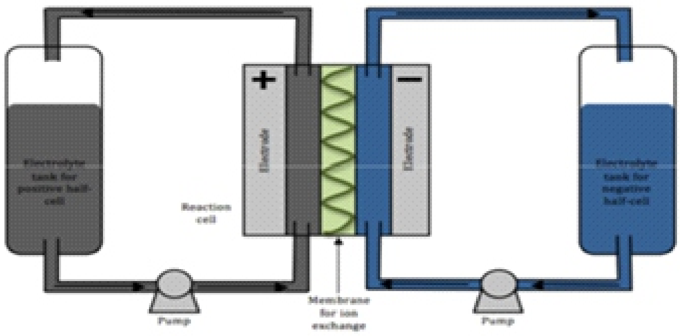


Fig. 6: Basic appearance of RFB

Analysis for Storage Battery Technologies Comparisons

The table 1 below shows the characteristic parameters used in the comparative analysis of battery storages technologies used for photovoltaic solar energy installations in residential applications.

Table 1: Battery energy storage Technology comparison table (Ohwofasa, 2018; Battery Council Internal, 2016; BRE & RECC, 2016; EASE/EERA, 2018; ECOFYS, 2014; IEEE, 2007; REA, 2016; Chao et al., 2018)

Technologies	Cost ($/KWh)	Efficiency (%)	Power Rating (MW)	Discharge Time	Lifetime (Years)	Self-Discharge per day (%)	Energy Density (Wh/I)	Power Density (W/I)
Lead Acid Battery	350-3800	80-90	0.001-100	1min-8h	5-10	01-03	50-80	90-700
Lithium-Ion Battery	900-6200	85-95	0.05-100	1min-8h	5-20	01-03	200-400	1300-10000
Sodium Surphur Battery	445-555	70-90	10-100	1min-8h	5-20	0.05-20	150-300	120-160
Redox Flow Battery	620-830	60-85	0.1-100	Hours	2-20	0-0.20	20-70	0.5-2

Comparison using average cost and average efficiency of the battery technologies

Table 2: Comparison using average cost and average efficiency

Technology	cost ($/kWh)	Efficiency (%)	Ave. Cost ($/kWh)	Ave. Efficiency (%)
Lead Acid Batteries	350 - 3800	80 - 90	2,075.00	85
Lithium-ion Batteries	900 - 6200	85 - 95	3,550.00	90
Sodium Sulfur Batteries	445 - 555	70 - 90	500.00	80
Redox flow Batteries	620 - 830	60 - 85	725.00	72.5

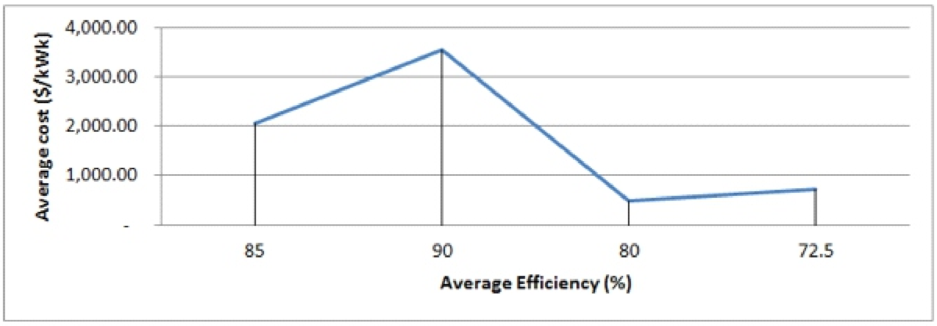


Fig. 7: Cost and efficiency

Comparison using Energy density and average Power density of the battery technologies

Table 3: Comparison using average Energy density and Power density

Technology	Energy density (Wh/l)	Power density (W/l)	Ave. Energy density (%)	Ave. Power density (%)
Lead Acid Batteries	50 – 80	90 - 700	65	395
Lithium-ion Batteries	200 – 400	1300 – 10000	300	5650
Sodium Sulfur Batteries	150 – 300	120 – 160	225	149
Redox flow Batteries	20 – 70	0.5 – 2	45	1.25

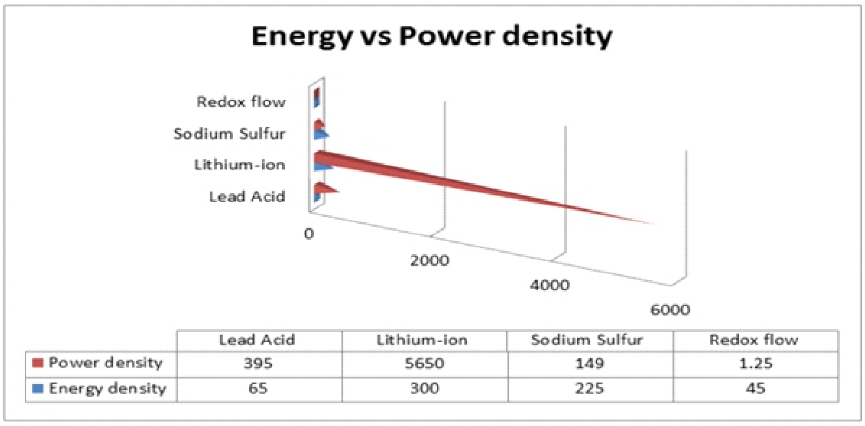


Fig. 8: Energy density and Power density

Comparison using battery technologies and average Self-discharge per day

Table 4: Comparison using battery technologies and average Self-discharge per day

Technology	Self-discharge per day (%)	Ave. Self-discharge (%)
Lead Acid Batteries	0.1 – 0.3	0.4
Lithium-ion Batteries	0.1 – 0.3	0.4
Sodium Sulfur Batteries	0.05 – 20	10.025
Redox flow Batteries	0 - 0.20	0.20

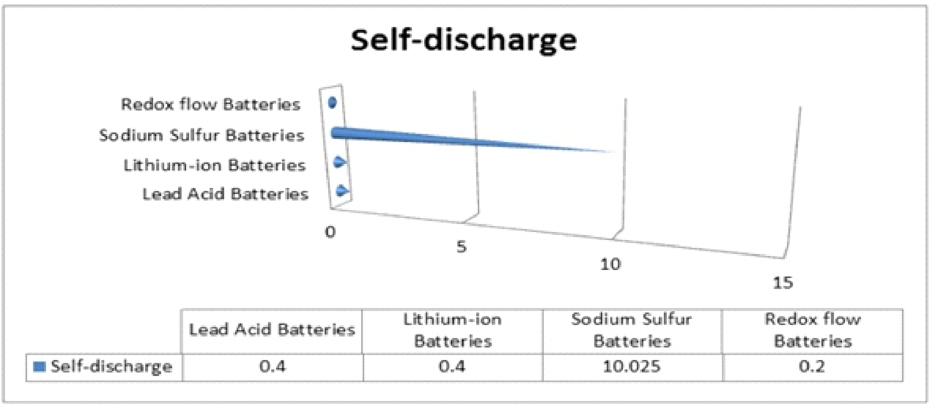


Fig. 9: Battery technologies and average Self-discharge per day

Comparison using average cost and average power rating

Table 5: Comparison using average cost and average power rating

Technology	cost ($/kWh)	Power rating(MW)	Ave. Cost ($/kWh)	Ave. Power rating (MW)
Lead Acid Batteries	350 - 3800	0.001 – 100	2,075.00	50.0005
Lithium-ion Batteries	900 - 6200	0.05 - 100	3,550.00	50.025
Sodium Sulfur Batteries	445 - 555	10 - 100	500.00	55
Redox flow Batteries	620 - 830	0.1 - 100	725.00	50.05

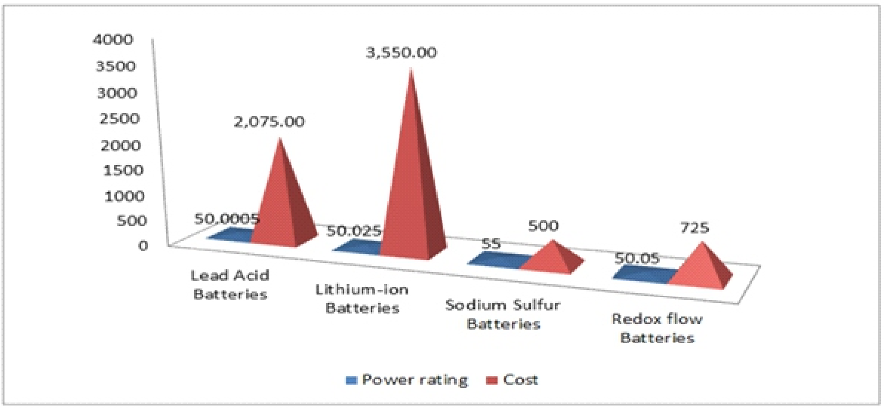


Fig.9: Cost and average power rating

Findings and Result of Analysis

The comparison of four Batteries Storage Technologies (Lead acid, Lithium ion, Sodium-Sulfur and Redox Flow) used for photovoltaic solar energy installations in residential applications that are commercially available was carried out. The results and findings in this subsection dealt with the average percentage range of the batteries cost, efficiency, energy density, power density, self-discharge per day and power rating as presented in table 1, 2, 3, 4 and 5. The comparison in terms of cost and efficiency shown in table 2 and figure 6 of the battery technology, pointed out Lithium-ion Battery with the highest average efficiency of 90% follow by Lead Acid Battery with 85% having the average cost of $3,550 and $2,075 respectively. And Sodium Sulfur and Redox Flow Batteries had 80% and 72.5% with average cost of $500 and $725 respectively. Though cost alone is not the only indicator for suitability others variables has to be considered. Table 3 and Figure 7 of the Energy density and Power density batteries comparison shown also the Lithium-ion battery dominating with the peak percentage of Energy density (5650Wh/I) followed by lead acid of 395Wh/I and Power density (300W/I) seconded by sodium- sulfur of 225W/I while Redox flow with the lowest in both (1.25Wh/I and 45W/I). The Self-discharge per daycomparison of the batteries in table 4 and figure 8gives illustrations of Sodium Sulfur having the highest percentage of 10.025% with Redox flow having the least of 0.20% while Lead Acid and that of Lithium-ion Battery having similar range of 0.4% each. Also, from table 5 and chart in Figure 9, the Sodium Sulfur and Redox flow Batteries have moderate cost with initial power rating higher than Lithium-ion and Lead Acid.

Conclusion

Battery technologies designed basically for the purpose of energy storage are becoming more and more part of those with the knowledge and the advantages it possesses. However, the question to ask now is, there are batteries but which is more durable and reliable for photovoltaic solar energy installations in residential applications? Due to the irregular and unpredicted nature of photovoltaic solar energy generation and the need to store up excess energy generated; battery storage is required. The study specifically focuses on four battery technologies (Lead acid, Lithium ion, Sodium-Sulfur and Redox Flow) that are commercially available.

Based on the findings of this study, the following conclusions can be drawn:

i. All the battery technologies in the study can be used for the storage of energy purpose with some having limitations.
ii. The Lithium-ion battery technology is the more reliable and most widely used technology as a result of its high efficiency, as reliability of any battery product is mostly based on the efficiency.
iii. It also has a high energy density, power density, moderate self-discharge, power rating, and manufacturing flexibility.
iv. It charges and discharges faster but relatively expensive among others.
v. Also, if the battery application requirements and the dangers in operating at a not required specification are ever taken into consideration, the Lithium-ion battery technology with its fast technological development will become the future energy storage solution.

Recommendations

i. Battery Energy Storage Technology is a preferred continues and future technology. Today energy contributes to economic growth of any nation, to avoid wastage and shortage of energy, more studies on battery energy storage technology is important. Though, a lot of research is ongoing as technology grows every second of the day. Although some battery energy storage technology has practically shown their reliability but not all can complete an ideal EST requirements, some are still either undeveloped or not commercially used. Continuation of future studies from the end of this study is recommended within a near future in order to fill the technical numeric gaps recorded in this study.

ii. The Lithium ions batteries are expensive but more studies can still be done on production and installation process to help in reducing the cost. Further in-depth study on battery energy storage technology manufacturing and engineering improvements, wider deployment and commercialization is recommended to lower costs of installation, better the numbers of cycles, improve longer lifetimes, and performance improvement to further lessen the cost of stored energy services.

iii. The Negative (Anode) plus positive (Cathode) electrodes, electrolyte and separators are the key operational active material of the battery technology that determine the functionality or efficiency of the battery. For the sake of future study, more detailed research on battery materials is recommended most especially the Graphene material that has good electricity conductivity and lighter in weight.

iv. More research is required into the initial and later costs of renewable energy and their power efficiencies should be put into consideration and encouraged.

v. Government should make provision for regular funding of researches on battery storage technology and development initiatives in tertiary institutions research bodies and Research Institutes.

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