Leveraging Storage Batteries for Sustainable Green Energy Harvesting: From Li-Ion Perspective

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Abstracts: To manage a power system with substantial proportions of renewable energy resources consistently and cost-effectively, the fast growth of green electricity necessitates a more flexible energy system. Energy storage is the sole technology that can offer energy shifting, from periods of surplus to periods of deficiency, improving the reliability and cost-effectiveness of renewable energy sources. In this frame of reference, a complete study of the techno-economic analysis and environmental evaluation of battery energy storage systems is presented here. This article provides a comprehensive examination of lithium-ion batteries (LIBs) as a potentially valuable technology for the energy storage sector. In this article, we examine the chemistry behind the most important developments in modern and future battery technologies. We discuss the ways in which LIBs are developing to accommodate the expanding field of energy harvesting. In addition, the article examines the economic and ecological challenges that are inherent with the production, distribution, and disposal of these batteries.

Keywords: Battery Energy Storage Systems, Economical and environmental effects of energy storage, Energy storage technologies, grid scale batteries, performance of utility scale batteries

1. INTRODUCTION

Global need of energy is continuously increasing day by day. This need has promoted increased penetration of renewable energy into the energy distribution network. The growing usage of RES, along with technical improvement, has resulted in the rise of storage as a critical component of energy management. [1] [2] [3] The intermittent nature of these sources makes deployment of energy storage systems obligatory to increase penetration and maintain power quality. Electrochemical energy storage batteries offer the most appealing options considering the advantages offered by these systems over other alternatives. BESS can overcome many challenges related to utility grid integration of RESs. This includes frequency regulation, peak shaving, load leveling, and black start capability. [4] [5] The economic storage of electrical energy remains one of the challenges of our modern society that has not yet been resolved. Finding a cost-effective and efficient method for massive volumes of energy storage is essential for the growth of renewable energy sector.

BESS is a competent solution over other storage technologies that are traditionally used for various range of applications, due to its small size, ease of deployment, virtually instant response, and economics.
Different electrochemical battery types that are used in grid energy storage include lead acid, Sodium Sulphur, lithium-ion (Li-ion), lithium iron phosphate, and flow batteries. Batteries such as Lead acid have been in use for decades and are the most prevalent form of grid energy storage battery by the virtue of their low cost and high energy density [6]

Batteries and fuel cells are similar, with the exception that when energy is needed, the active material is injected into the cell from an external source. Batteries store energy in the active material, while in fuel cells conversion of chemical energy into electrical energy occurs by reaction of an external fuel with an oxidant.

With technological developments over the past few years, the most pervasive and mature type seems to be lithium-ion batteries. In recent years, LIBs have accounted for the majority of market growth. By supplying backup power, balancing loads, and offering a number of other energy management services, storage technologies contribute to the strengthening and stabilization of the grid. This increased reliance on LIBs has revolutionized the energy sector by enabling the transition to a cleaner and more reliable grid infrastructure. Operational energy storage projects are increasing globally, the contribution of electrochemical batteries is also increasing and almost 90% of BESSs are contributed by LIBs fig.1 [7]

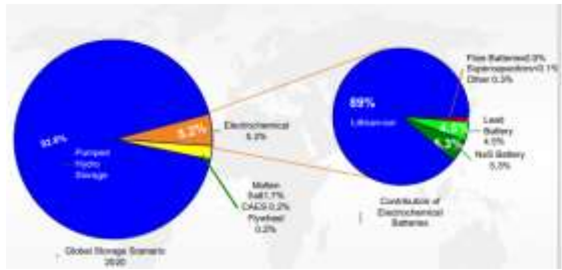

Fig.1 Global Operational Energy storage projects Source: CNESA Global Energy Storage Project Database.

Internationally, the sharp drop in lithium-ion battery prices is expected to revolutionize how RESs such as solar PV and wind are integrated into the grid. Until recently, the high costs and poor round trip efficiencies of BESSs prevented widespread deployment. However, the increased use of LIBs in electric vehicles and consumer devices has increased worldwide manufacturing capacity, which has led to considerable cost reductions that are anticipated to continue into the upcoming years. The increase in BESS deployments in recent decades, for both small and big scale grid level, and behind-the-meter installation, can be attributed in large part to the dropping cost and high efficiency of lithium-ion batteries. As per BNEF price of lithium –ion battery has dropped by 80% from 2010 to 2018 and is projected to reduce more to 135$/kwh in 2022 to 65$/kwh in 2035.

The renewable energy installed capacity worldwide in 2021 was 3,064 GW, according to Trend Force. This emphasizes the requirement for energy storage to balance sporadicness. China has doubled the capacity in 2020 and is planning to make it tenfold by 2025. [8] The capacity increases from utility-scale projects in the United States have more than doubled by 2020. Japan's behind-the-meter storage installations continued to grow rapidly, and in 2020 they will have reached around 300 MW. [9] Behind-the-meter storage still has a significant market in Australia, but over the coming years utility-scale projects are anticipated to take the lead. The dominance of lithium-ion technology continues to grow as EV deployment has positive spillovers. According to the Net Zero by 2050 Scenario [10], installed capacity will increase by 35 times between 2020 and 2030, reaching 585 GW. In 2030, there will be an increase in battery storage capacity of almost 120 GW, up from 5 GW in 2020, representing a 38% annual growth rate. [10] [11] With the majority of all installed new capacity, LIB storage continues being the most popular and dominating type of battery storage.

2. LARGE-SCALE ELECTRICAL ENERGY STORAGE ON THE GRID: CONVENTIONAL APPROACH

ESS technology describes the method of changing energy from one form to another storable form and can subsequently be converted back in electrical energy when necessary. As a result, energy storage units serve as a backup or energy buffer to balance out power imbalances between the supply and demand sides. [3] Various energy storage methods are available and can be divided into groups based on how energy is stored and converted. [12] [5].

2.1. Flywheels - The Kinetic Battery:

Electrical energy is conserved in the form of kinetic energy, and converted back to electrical energy as and when required. [13].

Flywheel has been in use as energy storage since ages and can be seen as first mechanical energy storage technology [14]. This is an electromechanical device that stores electrical energy in the form of rotational kinetic energy, which is function of the rotational speed W and the rotor primary moment of Inertia. [15] Energy stored (E) is directly proportional to moment of inertia (I) and square angular velocity (ω) of the flywheel, as given in equ.1 [14]

$$E = \frac{1}{2} I \omega^2 \quad \text{------(1)}$$

In order to boost rotational speed and power densities, current research is concentrated on flywheel material, high-speed electrical machines, bearings with large carrying capacities, and flywheel array technology. High-capacity flywheels are required in electrical power systems to store energy. Average efficiency is about 75% but with this technique, long-term storage is not possible. [14] [16].

2.2. Pumped storage system

Pumped-storage power systems are reversible hydroelectric facilities. [5] [17] PHS functions by pumping water from a secondary reservoir located at a lower elevation into an upper reservoir where energy is stored when the system is overloaded. When electricity is needed, water from the top reservoir is discharged, and as it falls, it drives turbines that produce the power. PHS has a round trip efficiency of between 70 and 80 percent (measuring that 20 to 30 percent of the electricity is lost). [18] Availability of large quantity of water and geographic elevations are key factors to be considered before planning of this system. [19]

2.3. Compressed Air Energy Storage (CAES)

CAES device compresses air into a chamber while charging. This compressed air is used to run the turbines when required. [13] [20] This system has estimated efficiency of 70% with lifespan of approximately 40years. [21] Geographical constraints on location of CAES system restrict the actual implementation. [22] The first system ever put into operation was the 220 MW system at Huntorf in Germany in 1978. [5] [21]

2.4. Super capacitors:

In super capacitors, charges are stored electrostatically. [23] Peculiar structure of super capacitor provides outstanding capacitance. Selecting exact ratings of supercapacitors is necessary for any application. [23] [24] The charging / discharging time of a battery is estimated using an equation based on the ampere-hour (Ah) rating. Eq (2) relating ampere-hour and capacitance is given below

$$Ah = [(V_{min} + V_{max}) / 2] * [F / 3600] \quad \text{------- (2)}$$

Where
Ah – Ampere hour
V_{min} and V_{max} are terminating voltages
F -- Farad

The primary characteristics of SC are remarkable efficiency, low operating temperature performance, low maintenance requirements, and resistance to deep discharges, responsiveness, and great durability. Whereas the drawbacks of this system can be listed as, Low energy density, high self-discharge, and high cost. [23] [25] Although the technology is relatively new, it has been developing at a rapid rate and is thought to be a great way to regulate voltage [26] Voltage sag regulators in Japan are using these technologies more and more frequently.

2.5 GRID-LEVEL BATTERY TECHNOLOGIES FOR LARGE-SCALE ELECTRICITY STORAGE

Energy storage systems can be seen simply as reversible energy wells that are designed to be adaptive and beneficial to the grid, and their efficiency is determined by the degree of performance of the unit in proportion to a subjective set of factors. The challenge in determining the best applications for a certain energy storage technology is due to their wide range of capabilities. It is difficult to maintain a profitable energy storage facility with just one market function, hence running numerous applications simultaneously is a fundamental principle of energy storage operational strategy. ESSs were originally designed as backup to the system and function as a supplemental support to the utility. Yet, with technological innovation and continued study, ESS has now evolved an important element of the energy system. Because of the rapid development in RES grid integration, ESSs are currently being utilized todecrease the intermittencies and also to store extra energy to prevent energy spillage.

The starting parameters of the unit are the most fundamental level of description of an energy storage system, since these values stay constant regardless of use. The performance specifications of these batteries differ in energy density charging and discharging capabilities, power performance, safety and cost. Some of the most essential system parameters are discussed here. Technological performance metrics define the operational outcomes in relation to a specific technical attribute

2.6. Energy capacity

The amount of electrical energy in KWh that can be stored by the storage system. [27] This is the product of the rated power and the time required to discharge at rated power of the system.

2.7. Specific energy density

How much energy there is contained in a battery in relation to its volume is measured as its energy density and is expressed in Watt-hours/liter [27]

When comparing batteries of identical capacity, a battery with a better energy density will be lighter.

2.8. Power density

Power density refers to how much power a battery can deliver when needed. [27]

2.9. Specific Power

This indicates loading capability of the battery [27]. Water bottle Analogy can be used to explain these parameters. The size of bottle and spout diameter represent energy and power density, respectively. A large bottle can hold a lot of water (high energy density), and a large aperture can swiftly empty it (high power density). Huge opening and large bottle make the perfect pair.

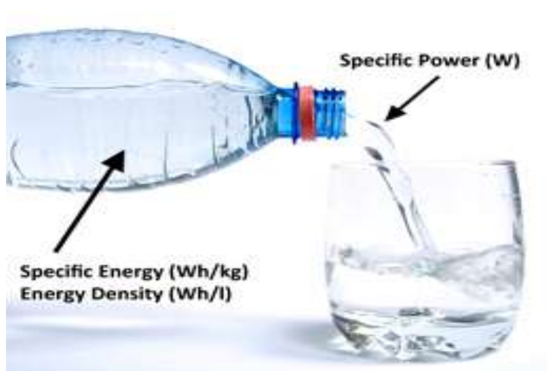

Fig 2: water bottle analogy to understand energy and power density

Considering the significant variation in electrical power demand, ESS is vital to maintain the grid's balance of electrical demand and supply. So ESS with quick reaction, extended cycle life, cheap cost, and high power and energy efficiency are required to satisfy requirements. [28] Driving factors for the deployment of BESS are Integration of clean energy, Economic rewards and energy security. [29] As the need for sustainable energy harvesting and storage has escalated, several battery technologies have emerged.

Grid scale batteries can be directly connected to transmission/distribution networks. Capacity of these batteries can vary from few MWh to thousands of MWh. Installation of Electrochemical batteries is rapidly increasing globally [30]

2.10. Lithium –ion battery:

This is rechargeable type of battery in which Lithium ions move through the electrolyte between the anode and the cathode and can create an electrical current when they flow from the anode to the cathode (fig 3) [13]

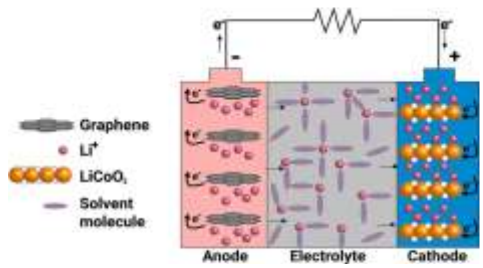

Fig 3: Schematic diagram of Li-ion Battery

While discharging, lithium ions are easily freed from the anode and absorbed into the delithiated cathode. During charging, this cycle is reversed, and the lithium ions travel back to the anode and store energy. [31] [27] This process is known as intercalation, and it allows lithium-ion batteries to be extremely efficient. The electro chemical reactions occurring in Li-ion batteries are.

At anode:

$$\Rightarrow Li_{(1-x)}CoO2_{(s)} + x\,Li+ + x\,e^{-} \quad LiCoO2_{(s)} \text{ --(3)}$$

Where x is number of electrons transferred in the reaction

The reaction at cathode is

$$LiCoO2 \leftrightarrow xLi+ + xe- + LixCoO2 \text{ -----(4)}$$

The charging and discharging of LIB can represented diagrammatically as in fig.4 (a) and (b)

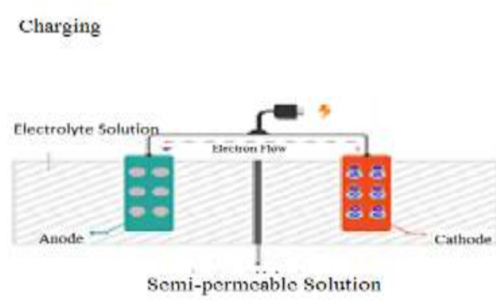

Fig 4: (a) Charging of Li-ion Battery

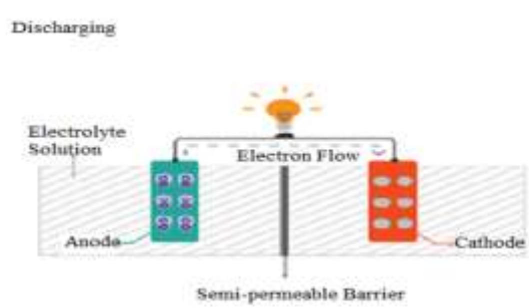

Fig 4: (b) Discharging in Li-ion Battery

In discharge process, lithium is oxidized from Li to Li + in the lithium-graphite anode. The electrolyte medium transports the lithium ions to the cathode, to be absorbed into lithium cobalt oxide. Reversing these processes will recharge the cell. While charging, the lithium ions are reabsorbed into the graphite matrix after being reduced to neutral lithium at the anode, which is made of lithium metal and graphite. [32]
The battery cell can be represented by an equivalent electrical model as shown

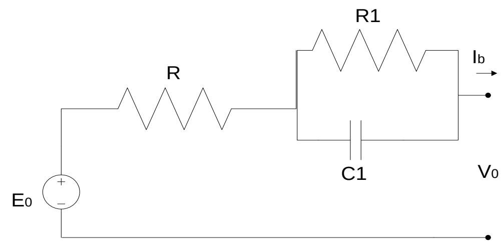

Fig. 5: Electrical model of battery cell

E_0 is the internal EMF when the battery is fully charged. It depends on battery temperature and state of charge (SoC) of battery. R, R_1, C_1 represent dynamics of the battery in all conditions.
Equation 3 represents the internal EMF of battery [33]

$$E_0 = V_0 - KE\,(273 + \theta) \cdot (1 - SOC) \text{ ---------(3)}$$

Where,
V_0 ----- no-load voltage at full charge, V;
KE ---- temperature coefficient, V/◦C;
θ ---- electrolyte temperature, ◦C;

$$R1 = -R10 \ln(DOC) \text{ ----(4)}$$

R_1 represents the change in resistance with depth of charge. As battery discharges, this value increases exponentially. C_1 represents transient process when the battery current changes. It is calculating as

$$C_1 = \tau_1 / R_1 \text{-------(5)}$$

Where,
τ_1 ---- time constant for the branch

Recently in 2019 The Noble Prize in Chemistry was a awarded to John B. Goodenough, M. Stanley Whittingham and Akira Yoshino for their significant research on lithium –ion batteries. [34] The milestones in the evolution process of Li battery are shown in Fig 6 to shed some light on understanding the evolution and development of this battery. [35]

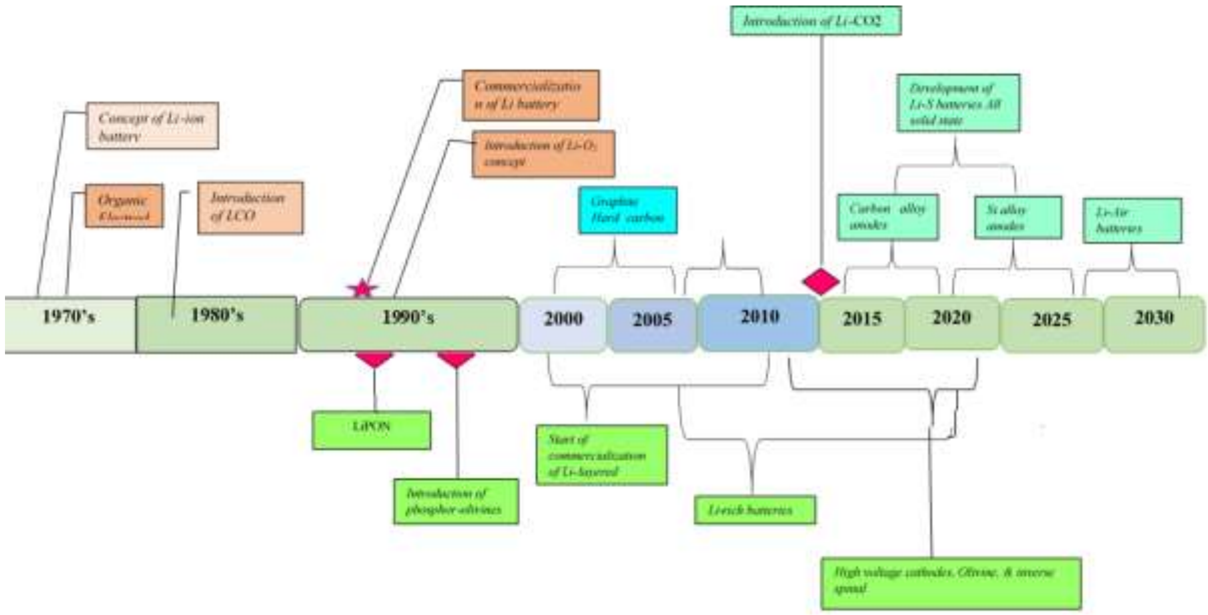

Fig. 6: Technical evolution of Li-ion Batteries

Performance of Li-ion battery changes significantly with different cathodes. [36] Cathodes of Li-ion are made up of different a complex delithiated material, specifically lithium metal oxide materials like LiCoO2, LiMn2O4, and LiFePO4. Among the three insertion-compound cathodes currently in play, the layered oxides can provide the highest energy density [37] [31] [38] [36] utilisation of graphite as an anode in lithium-ion batteries is very popular due to its low cost, good electrical conductivity, and a capacity of up to 372 mAh/g Lithium salts like, propylene carbonate, ethyl methyl carbonate, ethylene carbonate dimethyl carbonate, and their mixtures, form the liquid electrolyte for LIBs. [37] These liquid electrolytes are highly conductive due to the presence of lithium salts, and they provide ionic conduction pathways between the anode and cathode.

Different types of lithium –ion chemistries are available with each one having different characteristics. Characteristics of these batteries differ mainly due to type of material used for electrodes. Some of the examples are LCO, LMO, NMC, LFP batteries. Comparison of characteristics of these batteries is shown in the following tables [37] [39] [36] [40]

Table 1: Summary of Positive Electrode Material Characteristics

Material	Specific Capacity (mAh/g)	V vs. Li (at 0.05C)	Advantages or disadvantages
$LiCoO_2$ Lithium Cobalt	155	3.88	Cobalt is costly
$LiNi0._7Co0_3O_2$	190	3.70	moderate price
$LiNi0._8Co0._2O_2$	205	3.73	moderate price
$LiNi0._9Co0._1O_2$	220	3.76	highest specific capacity
$LiNiO_2$	200	3.55	Most exothermic decomposition
$LiMn_2O_4$ Lithium	120	4.00	Mn is at lesser cost, less toxic,

Manganese oxide			decomposition due to exothermic reaction is less

Table 2: Characteristic comparison of different Li-ion chemistry batteries

	Lithium Cobalt oxide $LiCoO_2$	Lithium manganese oxide $LiMn_2O_4$ LMO	Lithium Nickel Manganese Cobalt Oxide NMC	Lithium Iron Phosphate $LiFePO_4$ LFP	Lithium Nickel Cobalt Aluminum Oxide $LiNiCoALO_2$	Lithium Titanate Li_2TiO_3 LTO
Cathode	Cobalt oxide	$LiMn_2O_4$	$LiNiMnCoO_2$	$LiFePO_4$	$LiNiCoALO_2$	NMC or lithium manganese oxide
Anode	Graphite	Graphite	Graphite	Graphite	Graphite	Li_2TiO_3
Voltage	3.60V	3.70V	3.60 -3.70V	3.20-3.30V	3.60 V	2.40V
Specific energy	150-200Wh/kg	100-150Wh/kg	150-220 Wh/kg	90-120Wh/kg	200-260Wh/kg 300Wh/kg Predicted	50-80Wh/kg
C-rate Charge	0.7-1C 4.20V	0.7-1C 4.20V	0.7-1C 4.20V	1C 3.65V	0.7C 4.20V	1C 1.80V
C-rate Discharge	1C 2.50V	1C 2.50V	1C 2.50V	1C 2.50V	1C 3.0V	10C 1.80V
Cycle life	500-1000	300-700	1000-2000	2000 and higher	500	3000-7000
Thermal Runaway	150^0 C	250	210	270	150	Safe battery
Drawback	minimal lifespan minimal thermal stability restricted capacity for loads	Safe than Li-cobalt; frequently combined with NMC to enhance performance; high power, lower capacity	Large capacity and power. Acts as a hybrid cell Preferred chemical for numerous applications	Low capacity very flat voltage discharge curve. most secure Li-ions		wide temperature range, quick charging, and long life, but pricey and poor specific energy Ones of the safest Li-ion batteries
Applications	Mobile phones laptop tablets, Camera	Power tools Electric power trains	E-bikes, medical devices, EVs, industrial	Portable and stationary need high load currents and Tolerance Used primarily for energy storage	Medical devices, industrial, electric powertrain	UPS, electric powertrain

High energy density, longer life and higher energy efficiency and slow discharge rate of Li-ion battery make these type of battery a preferred choice in grid-scale energy storage systems. Since the introduction in early 1990 by Sony, these batteries have emerged as one of the most significant technologies, dominating the market. [41]
Recently, significant attempts have been undertaken to optimize graphite-based anode materials, and few new anode materials, like silicon, alloys, and metal oxides, have been developed. Recent efforts to optimize graphite-based anode materials have led to the development of new anode materials, such as silicon, alloys, and metal oxides, which have improved battery capacity and life time. [39] [42]

Recent studies have shown that with technological improvements the energy density of LIB battery has improved almost by 82% since 2008 to 2020. Increase in energy density facilitates to draw more energy to drawn from batterypack of same weight. Following graph (Fig, 7) shows the ascent in energy density of LIB. [43] [44]

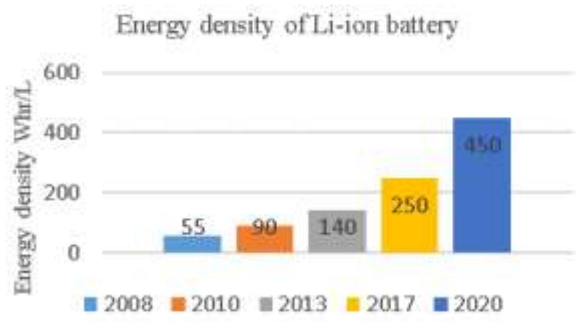

Fig 7: Improvement in energy density of Li-ion battery

Other electrochemical batteries that dominate the energy storage market include lead acid battery, Nickel cadmium and sodium Sulphur batteries to name a few. A brief discussion about these technologies is followed.

2.11. Lead Acid (Pb-A) battery

The lead-acid battery is a long-standing battery technology. [45]Lead oxide serves as the active positive electrode material for this device, and metallic lead serves as the active negative electrode material. As an electrolyte, sulfuric acid solution is utilized. A significant component affecting the performance and endurance of lead-acid batteries is the positive active material, which is electrochemically created from the cured plate. The negative electrode, often known as the lead electrode, typically regulates cold-temperature performance. Since the charge-discharge process is essentially reversible, no harmful chemical reactions occurs in the system. [28] [46] The functioning of the Pb-A battery is represented by the equation.(5) [46] [47]

$$Pb + PbO_2 + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O \quad \text{with } E^0 = 2.04V \text{ -------(5)}$$

Its inexpensive price combined with strong performance and a long cycle life is a big reason for its ubiquity. [48] To benefit from the affordability of this battery, load balancing for utilities and solar PV Systems can be included. But, it will be necessary to increase the lead-acid battery's energy and power density for these applications. [49]

2.12. Flow Batteries

Flow battery is an electrochemical cell where energy is stored in liquid electrolyte. Various flow battery systems based on different chemistries are commercialized and some are still at being researched. The more successful pair of electrodes are liquid/gas-metal and liquid-liquid electrode systems based on the electro-active materials used in the system

The commercialized flow battery system Zn/Br is a liquid/gas-metal electrode pair, whereas the All-Vanadium Redox Flow Battery (VRFB) is a liquid-liquid electrode pair. Similarly, some technologies, such as V-Br, Zn/V are being researched in the laboratory prototype stage. V-Br has advantage of low material cost and improved RTE. [50].

Aqueous zinc-based RFBs are promising for utility-scale energy storage applications because of their high safety, with low cost, and eco- friendliness, however, zinc dendritic growth has reduced cycle performance, stability, and efficiency, preventing zinc-based redox flow batteries from being commercialized. [51]
Flow batteries provide long-lasting, rechargeable energy storage, particularly for grid reliability. In a recently published work β-cyclodextrin, a derivative of starch when used as additive, enhances the battery longevity and capacity. [52]

2.13. Vanadium redox-flow battery

Popularly known as VRB, this battery is a cutting-edge energy storage device used in power grid applications. The battery is distinguished by the use of the same chemical element in both the anode and cathode electrolytes. A standard RFB is made up of energy storage vessels, an electrochemical cell stack, and a flow system. In the external tanks, liquid electrolytes are stored as catholyte and anolyte. Ions move through the membrane that separates two stacks Charge is added or withdrawn from the reactant tanks via a membrane as the catholyte or anolyte is cycled. [53] [54] The battery takes advantage of vanadium's ability to prosper in four distinct oxidation states in solution to create a battery with just a single electroactive component rather than two. Sulphuric acid is used as electrolyte which enhances the solubility of vanadium species. It also provides the protons for the flow of electric current in the cells and balances the main reactions of the battery. [54] [55] The electrolytes circulate back to their respective tanks after pumping into the stack for electrochemical reaction.

Numerous flow battery designs have been developed, and a few have been implemented in commercial settings. However, it is worth noting that the current commercial installations predominantly depend on the utilization of mined minerals, such as vanadium, which pose significant challenges due to their high cost and limited availability. [56] Hence, research teams are currently endeavoring to identify efficacious alternative technologies that employ readily synthesized, stable, and non-toxic materials.

2.14. Zinc Bromine Flow Battery (ZBFB)

Aqueous solutions of zinc bromide are employed as both a catholyte and anolyte. A positive electrode is made of bromine dissolved in a solution, and a negative electrode is made of solid zinc deposited on a carbon electrode. Hence ZBFB is also known as hybrid flow battery. [57]
At Positive electrode

$$Br + 2e^- \Longleftrightarrow 2Br, E = +1.09 V$$

At Negative electrode

$$Zn^- \Longleftrightarrow Zn + 2e , \; E = -0.76V$$

The aforementioned battery exhibits several notable advantages, including a high energy density, the ability to generate high voltage, and the utilization of a low-cost electrolyte. However, one of its drawbacks is its limited lifespan and potential safety concerns. Additionally, the process of recharging zinc dendrites is time-consuming, and an excessive release of Br2 leads to a decrease in battery capacity.

2.15. Zinc air

The progress of alkaline-based Zn-air batteries has been impeded by parasitic reactions occurring at the Zn anode and sluggish oxygen redox kinetics, despite their favorable attributes such as high energy density, low cost, and abundant materials. The slow reaction rates result in a significant disparity between the theoretical and practical energy density. [58]

Recent years have seen extensive study devoted to the creation of effective oxygen electro catalysts, which may prove useful in overcoming these obstacles. Recent advancements in nanotechnologies, is boosting efforts in upgrading ORR/OER kinetics to improve practical energy density of ZABs [59]

2.15. Solid State Li-ion Battery

Li-ion battery with solid electrolyte is known as solid state Li-ion battery. Solid electrolyte acts as separator. These batteries not only solve the major safety problems plaguing commercial lithium-ion batteries but also have more room to grow in terms of energy density. Recent studies have shown that lithium zirconium oxychloride (LZCO) which is synthesized from compounds such as lithium chloride, lithium hydroxide monohydrate, and zirconium chloride poses to be a competitive alternative in terms of economics. Experimental evidence suggests that LZCO is on par with the most sophisticated sulphide and chloride solid-state electrolytes currently on the market. [60] [61]

2.16. Nickel Cadmium (NiCd)

One of the most widely used alkaline batteries, it comes in a variety of cell configurations and cell sizes. The battery has positive plates with NiOOH as the active component, negative plates with finely divided cadmium metal as the active component, and a potassium hydroxide (KOH) in water electrolyte in the charged state. [28] [27] [47] The Charging and discharging reaction can be defined by the following equation. [62]

$$2NiOOH + 2H_2O + Cd \Longleftrightarrow 2Ni(OH)_2 + Cd(OH)_2 \quad \text{with } E^0 = 1.29\text{ V} \text{ ------(6)}$$

It is good for stationary application by the virtue of low cost, excellent discharging characteristics, and long life. But since cadmium is a poisonous metal, it is difficult to dispose of these batteries. Additionally, this battery exhibits memory effect, meaning that it only accepts a full charge following a string of full discharges. [63] Number of financial triumphs employing Ni-Cd batteries for deployment of EES at utility scale have been achieved. [64] As an example, the Golden Valley Electric Association deployed a 27 MW Ni-Cd BESS in 2003. [65]

2.17. Nickel-metal hydride (NiMH):

This NiCd alternative uses non-toxic ingredients, which results in a better energy density and greater environmental friendliness. This battery has been in market for more than 20 years but it is mainly used in small and portable applications. [28] [47] [66] It comprise metal hydride anodes, nickel hydroxide cathodes, and alkaline electrolytes The battery chemistry of Ni–MH battery can be represented as

$$MH + NiOOH \Leftrightarrow M + Ni(OH)_2 \quad \text{with } E^0 = 1.35\text{ V} \text{ -------(7)}$$

The basic versions significant self-discharge and dependence on the scarce supply of rare earth minerals are the downsides of this battery.

2.18. Sodium nickel chloride ($NaNiCl_2$ or zebra):

This is also known as ZEBRA batteries and are high temperature batteries operating at 270°C–350°C A beta-alumina ceramic wall, which works as an isolator for electrons but is conductive for sodium ions, separates the electrodes. [47] It acts as an electrolyte also and facilitate the transport of sodium ions from the cell's anode to its cathode. [62] In order to maintain the electrodes in a molten condition, the battery temperature is maintained between 270° C and 350° C; thus, heater becomes an integral part of the battery system. [67] The chemical reaction during battery charging and discharging is represented by

$$2Na + NiCl_2 \Longleftrightarrow 2NaCl + Ni \quad \text{with } E_0 = 2.58\text{V at } 300^0\text{ C} \text{ -------(8)}$$

This technology is compact and lightweight, with a quick response time, resistance to full discharge, and a very high energy density. Single battery capacity may ranges from 4 to 25 kWh Single battery capacities may be anywhere from 4 to 25 kWh, while total energy storage capabilities can be anything from a few Kwh to several Mwh.

[68] Due to the ceramic electrolyte, the battery does not suffer from self-discharge. Depending on the operating conditions, the internal electrical loss which is converted to heat, balances the thermal loss, resulting in an overall efficiency of between 80 and 95 percent. [67] [69] This technology is suitable for specific on-grid and off-grid applications. Initially introduced for automotive market, this technology is now being used applications like stationary energy storage, smart grid, renewables, backups etc

2.19. Sodium Sulphur (NaS)

First introduced in 1967, this battery is considered as one of the most encouraging options for large scale storage. Molten sodium and Sulphur acting as anode and cathode respectively separated by solid ceramic, sodium alumina acting as electrolyte this battery operates at high-temperature around 300^{0}C. [70] [71] Equation 9 lays forth the chemical reactions that occur throughout the charging and discharging processes of Na-S batteries. [28] [72]

$$2Na + xS \Longleftrightarrow Na_2Sx \qquad E^0 = 1.78\text{-}2.07 \text{ (V -9)}$$

It has quick switching between charging and discharging, effective operation, the ability to supply pulse power up to six times that of continuous power, low maintenance needs, a lengthy lifespan, and a high potential for scaling. Its requirement for a high operating temperature discharges it inadvertently, which is one downside. [73] Peak-shaving and electricity quality both benefit economically from it. According to some authors, the corrosion issues with this technique could reduce its dependability. [74] Key parameters of some of the batteries are compared in the following table [75] [76] [77] [78] [79] [80].

Table 3. summary of performance parameters of batteries used in grid scale integration

Specification/ Battery Type	Li-ion			Lead-acid	NiCd	NiMH
	Cobalt	Manganese	Phosphate			
Specific Energy Density (Wh/Kg)	150-190	100-135	90-120	30-50	45-80	60-120
Life Cycle (at 80% discharge)	500-1000	500-1000	1000-2000	200-300	1000	300-500
Charge Time	2-4h	1hr or less	1hr or less	8-16h	1 hr	2-4hr
Self Discharge/month	<10%			5%	20%	30%
Internal Resistance (m ohm)	150-300 7.2V	25-75 Per cell	25-50 per cell	<100 12V	100-200 6V	60-120 6V
Overcharge Tolerance	Low. It cannot tolerate Trickle charge			High	Moderate	Low
Peak load Current	>3C	>30C	>30C	5C	20C	5C
Cell Voltage	3.6V	3.8V	3.3V	2V	1.2V	1.2V
Charge Cutoff voltage	4.20		3.60	2.40	Full charge detection by voltage signature	
Charge temperature	0-45^0 C			-20-50 ^{0} c	0-45 ^{o} C	
Discharge temperature	-20 60 ^{o} C			-20-50 ^{0}C	-20-60 ^{0}C	
Safety requirement	Protection circuit is required			Thermally stable	Common fuse protection required. Thermally stable	
Toxic	Low			Very High	Very High	Low

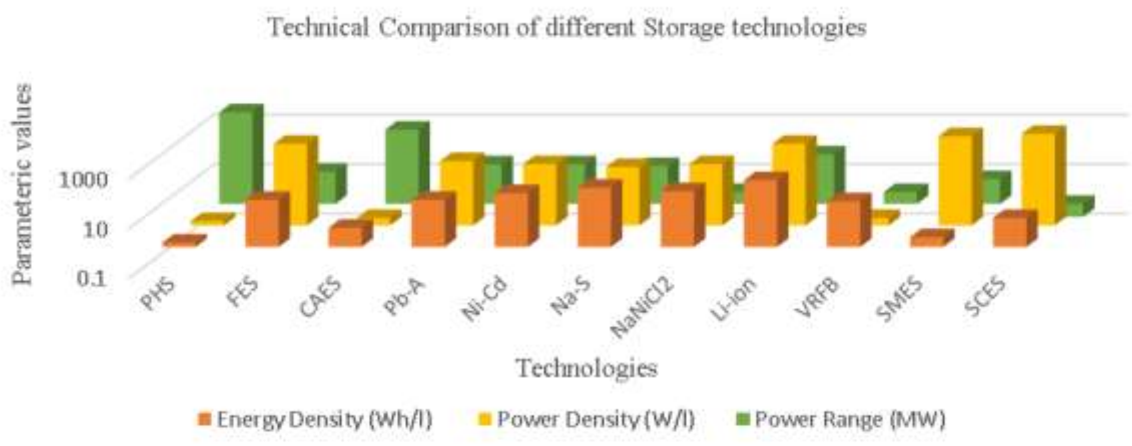

Fig 8: Technical Comparison of Different storage technologies

Comparison on the factors of energy density, power density and power range of different storage technologies is represented graphically in Fig.8. It can be seen that LIB is superior in all aspects compared to other batteries. These batteries come with different advantages and some disadvantages which can be summarized as in table 4. [37] [46] [79].

3. Economic factors:

An energy storage system's economic performance is a compromise between the most economical design and its operation strategy for a specific market role. [81] While designing any storage project economic factors make significant impact on developer's decision. Since the batteries need to charge or discharge for limited duration of time, maintenance of this state at any given time is of utmost importance. Active materials fade over time as a result of repeated charging and discharging cycles, which causes aging. Discharging below rated SOC or above rated DOD will age the Battery faster. [82] To carry out economic analysis of BESS maximum DOD should be kept up to 80% for maximum benefit of battery life. [83] And avoid degradation of performance. [84] Cost of BESS depends on many factors [85] [86]Fig.9

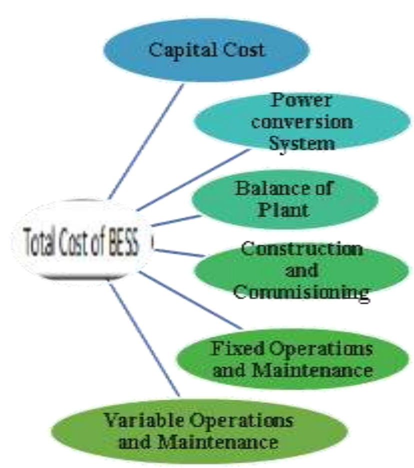

Fig. 9: Cost components of BESS

Feasibility of BESS project depends mainly on the cost of Battery which estimates to be 35% of total cost of project. Apart from this, the price of the BMS and the power conversion system is 35% of the total, and cost of construction of communication and distribution facility accounts 30%. [83] [86]

Ageing and cell chemistry are the two main factors that affect battery life. Electrode material, energy density, cell capacity, and energy to power ratio are the factors incorporated in cell chemistry. [79]

Currently, in many cases ESS is not feasible due to cost. But in coming decades as the contribution of renewable energy sources increases the cost of ESS is expected to reduce. [79]. [87] This decline in cost is calculated as levelized cost [83] [88] equation (10) and is projected graphically in Fig 10. Comparison of cost of different battery technologies in 2025 is projected in Fig.11. [85] It can be seen that capital cost of LIB will be comparatively lesser than other technologies of same capacity.

Levelized cost is calculated using the formula

$$LCOS(\$/KWh) = \frac{CAPEX}{\#Cycle \ast DOD \ast C_{rated} \ast \sum_{n=1}^{N} \frac{(1-DEG \ast n)}{(1+r)^n}} + \frac{O\&M \ast \sum_{n=1}^{N} \frac{1}{(1+r)^n}}{cycle \ast DOD \ast C_{rated}} \ast \sum_{n=1}^{N} \frac{(1-DEG \ast n)}{(1+r)^n} - \frac{\frac{V_{residual}}{(1+r)^n}}{Cycle \ast DOD \ast C_{rated} \ast \sum_{n=1}^{N} \frac{(1-DEG \ast n)}{(1+r)^n}}$$

Where
CAPEX is capital expenditure
N -------Project Life time
DoD ----Depth of Discharge
C_{rated} ----Rated Capacity
DEG----Annual degradation rate of capacity
r----------Interest rate
$V_{residual}$---Residual project value after lifetime

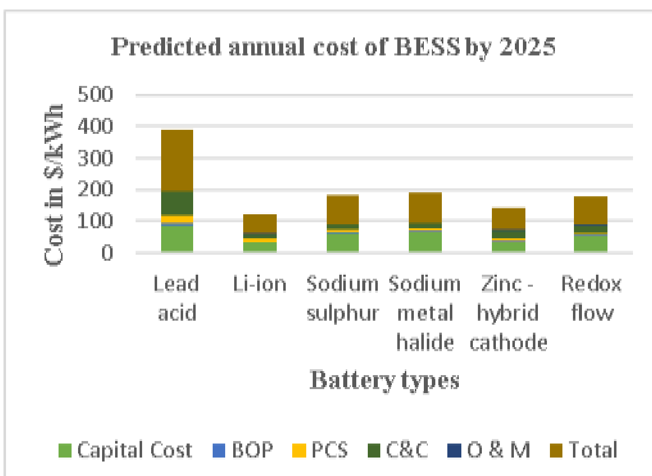

Fig. 10: Projected Cost of Li-ion battery

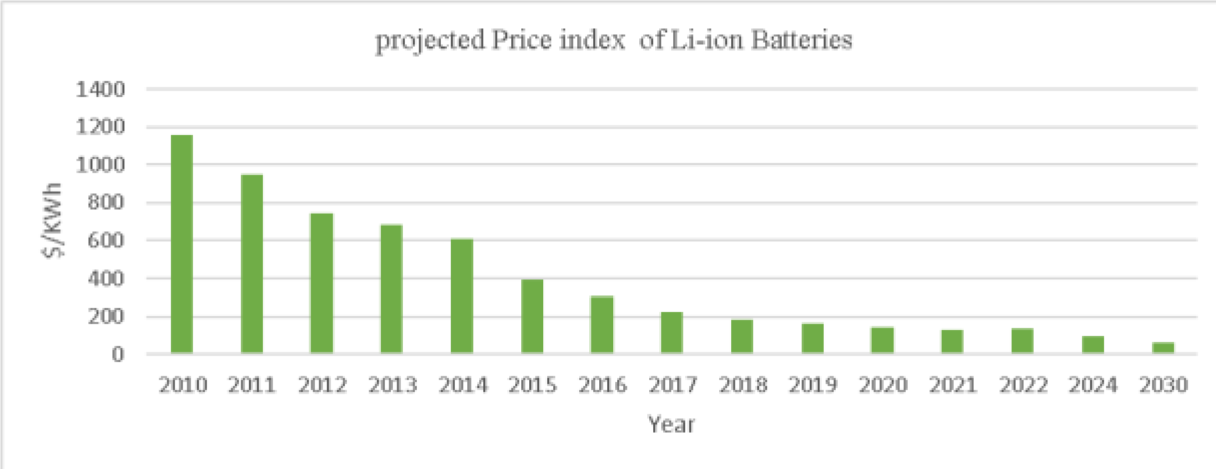

Fig. 11: Projected Total cost of Different Battery technologies in 2025

4. Recycling of Batteries

Materials used in battery manufacturing are toxic and can pose danger to environment and human life. [79] Batteries made of lead and cadmium provide the greatest environmental risks; [90]as a result, nickel-cadmium was forbidden in Europe in 2009. These batteries must be disposed off very carefully once its life is over. [91] Mechanically crushing the batteries and with further processing the electrolytes used can be recovered for reuse. [79] [92] But this recycling process is energy intensive and sometimes can consume more energy than required for extraction of it from mine. [79] The basis for effective recycling was laid by lead acid batteries, out of which lead can be removed and reused without the need for complex procedures. These batteries are now recycled in the USA at a rate of well over 97 percent. The supply of lead is made up of recycled batteries to a greater than 50%. If large quantity is available, then nickel from NiMH can also be recovered economically.

Li-ion batteries are included in the list of contaminants very [93] recently. Although this chemistry deemed to mildly hazardous, its large quantity calls for closer examination. Li-ion battery recycling needs government assistance because it is not economically viable yet. Currently no recycling technology is available to retrieve pure Lithium that can be subsequently used in batteries. Recovery of expensive cobalt is also encouraged. [94]

Recycling technology for lead acid batteries is enough matured and nearly 70 percent of the battery weight can be recycled. Due to near complete recycling, this battery is no longer listed in the list of harmful batteries. *[95]* Attention is now being paid to recycle Li-ion battery due to rising quantity and value of recyclable material.

New cost effective and less harmful methods like chemical recycling are being developed to retrieve the metals. *[79]* Batteries containing dangerous materials will always be around, but using them is acceptable as long the batteries are disposed of appropriately. Environmental impact of storage systems if weighted on the scale of 10 can be represented by fig.12.

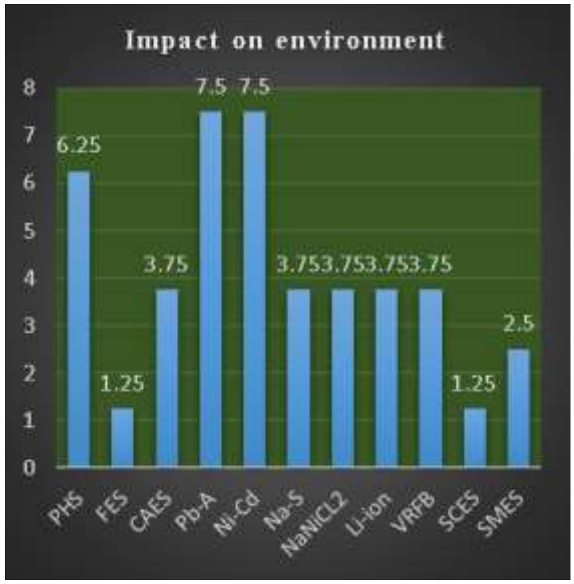

Fig. 12: Impact of storage technologies on environment

5. Real life Projects of BESS

A few examples of batteries adding value and delivering services in the real world for large-scale grid applications, BESS has been deployed in a number of different ways.

Even though 64.7% of the total power capacity projects are categorized as 'Electro-chemical' more than two third of it is contributed by Li-ion battery. Other contributors are very small in quantity but these batteries have their own niche market even though insignificant.

Table 5. *Real life Projects of BESS*

Project name	BESS Capacity	Location	Service rendered
Hornsdale Power Reserve [87] [1]	100 MW/129 MWh lithium-ion battery	South Australia since December 2017	Contingency reserve
Vermont's Green Mountain Power project	4 MW lithium-ion	September 2015	Integration with microgrid, Load balancing, backup power
Solar River Project [96]	A 100MW - 400MWh	South Australia, 2021	Reservoir grid storage system with the 200MW Solar
NSW's Hunter Valley	1,200 MW battery	expected to be completed by 2023	
STEAG's battery storage project [1]	90 MW / 120 MWh	Germany	Frequency regulation

Terna [1]	38.4 MW / 250 MWh Sodium-Sulphur battery	Italy 2017	Reduction in T & D infrastructure development voltage control & Load balancing
NGK Insulators [1]	34 MW / 204 MWh sodium Sulphur battery storage system	Rokkasho, Aomori, Japan	Spinning reserve Frequency regulation
Secretariat of the Pacific Community	1.5 MWh battery with 270 kW solar PV	Yap State, Federated States of Micronesia	Cost reduction on diesel generators
Glassenbury and Cleator [1]	40MW & 10MW	United Kingdom	Improved frequency regulation
AES-SDG&E Storage Project [1]	30 MW / 120 MWh Li-ion battery	California, U.S.A.	Store excess electrical energy Capacity reserve
San Juan Capistrano [1]	2 MW / 6 MWh	California, U.S.A.	Peak demand offset Avoid T & D upgradation
Renewable Energy Systems and Utility of Ohio's battery storage project [1]	4 MW / 2.6 MWh	Columbus, Ohio, United States	Frequency regulation
Tata Power-DDL [87]	10 MW/10 MWh Li-ion Battery	Rohini (Delhi) India	grid stabilization Peak load management system flexibility, enhance reliability

6. Conclusion:

Recent studies have projected that there is significant growth in electricity generation by renewable energy sources and if countries continue to increase their current energy percentage of renewable energy in the global energy sector, the capacity of all electrical storage will triple by 2030. To ensure significant improvement in storage technology, specifically battery energy storage systems and seize the advantages related to grid-scale applications of BESS, some of the issues that must be addressed are listed below

1. Reduction in cost: Cost is an important component of battery energy storage system. Recent developments in storage technology has shown significant decrease in the cost and is predicted to decrease by 54-60% by 2030 with lead –acid batteries and lithium batteries going neck to neck. Apart from reduction in cost performance indices like increase in battery life and number of cycles must be taken care of. Thus improving the overall efficiency.

2. Ore extraction and disposal policy: Electrochemical batteries use some harmful components for chemical reactions. Such batteries pose danger to environment and human life if disposed off carelessly. Advanced methods of extraction of raw material and recycling techniques for disposal of used batteries must be designed and developed to reduce environmental impact. Disposal policies must be defined and monitored stringently by the authorities to reduce ecological impact.

3. Exploring new cutting edge battery technologies: Research on energy storage systems for utility grids should focus on improving battery performance, including energy and power capacity, number of operating cycles, operating voltage, safety, eco-friendliness, and cost. It should also focus on developing methods to reduce the total cost while maintaining its other features. Battery technologies like sodium Sulphur and sodium nickel have been around for a while, but it is only in recent years that their potential as efficient energy storage solutions has been widely recognized. Monocrystalline cathodic material is being used to improve the durability of lithium-ion batteries, making them more durable and able to withstand multiple charging cycles.

4. Comprehensive assessment: A smart power grid incorporates power plants on a vast scale and applications scattered globally with diverse climatic factors, temperatures, and geographical locations. Battery performance should incorporate technical qualities as wel as cost, safety, and environmental effect. Additionally, evaluating and comparing battery technology using the same criteria is crucial. As a result, comprehensive assessment should consider all these factors in order to develop the most efficient and cost-effective smart power grid.

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