Hindawi
Journal of Renewable Energy
Volume 2024, Article ID 2329261, 35 pages
https://doi.org/10.1155/2024/2329261

Review Article

A Review on the Recent Advances in Battery Development and Energy Storage Technologies

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Received 27 June 2023; Revised 9 February 2024; Accepted 24 April 2024; Published 8 May 2024

Academic Editor: Ponnusami V.

Energy storage is a more sustainable choice to meet net-zero carbon foot print and decarbonization of the environment in the pursuit of an energy independent future, green energy transition, and uptake. The journey to reduced greenhouse gas emissions, increased grid stability and reliability, and improved green energy access and security are the result of innovation in energy storage systems. Renewable energy sources are fundamentally intermittent, which means they rely on the availability of natural resources like the sun and wind rather than continuously producing energy. Due to its ability to address the inherent intermittency of renewable energy sources, manage peak demand, enhance grid stability and reliability, and make it possible to integrate small-scale renewable energy systems into the grid, energy storage is essential for the continued development of renewable energy sources and the decentralization of energy generation. Accordingly, the development of an effective energy storage system has been prompted by the demand for unlimited supply of energy, primarily through harnessing of solar, chemical, and mechanical energy. Nonetheless, in order to achieve green energy transition and mitigate climate risks resulting from the use of fossil-based fuels, robust energy storage systems are necessary. Herein, the need for better, more effective energy storage devices such as batteries, supercapacitors, and bio-batteries is critically reviewed. Due to their low maintenance needs, supercapacitors are the devices of choice for energy storage in renewable energy producing facilities, most notably in harnessing wind energy. Moreover, supercapacitors possess robust charging and discharging cycles, high power density, low maintenance requirements, extended lifespan, and are environmentally friendly. On the other hand, combining aluminum with nonaqueous charge storage materials such as conductive polymers to make use of each material's unique capabilities could be crucial for continued development of robust storage batteries. In general, energy density is a key component in battery development, and scientists are constantly developing new methods and technologies to make existing batteries more energy proficient and safe. This will make it possible to design energy storage devices that are more powerful and lighter for a range of applications. When there is an imbalance between supply and demand, energy storage systems (ESS) offer a way of increasing the effectiveness of electrical systems. They also play a central role in enhancing the reliability and excellence of electrical networks that can also be deployed in off-grid localities.

1. Introduction

In order to mitigate the current global energy demand and environmental challenges associated with the use of fossil fuels, there is a need for better energy alternatives and robust energy storage systems that will accelerate decarbonization journey and reduce greenhouse gas emissions and inspire energy independence in the future. Of great interest is the design and fabrication of low-cost and sustainable energy storage systems which are the epitome of efficient energy harvesting from renewable energy sources such as the sun and wind. Only a few of the world's power capacity is currently stored. It is believed that by 2050, the capacity of energy storage will have increased in order to keep global warming below 2°C and embrace climate adaptation. To accomplish this projection, creative means of accelerating the green energy uptake and renewable energy access must be advanced. Consequently, the provision of clean, green, inexpensive, environmentally friendly, and abundant energy to the world is one of the main challenges mankind encounters in the 21st century. It has been noted that, in comparison to other fuel sources, solar photovoltaics and solar thermal are anticipated to offer practical solutions in the future. In comparison to other fossil commodities, renewable energy is especially significant because it is more likely to produce the highest annual results. Despite its benefits, energy storage still faces a number of obstacles to widespread adoption, including high costs, lack of incentives, and technological challenges. Moreover, compared to conventional production sources, energy storage technologies are pricey and they frequently do not get paid enough for the benefits they offer. Energy storage systems allow for the storage of extra energy during periods of high production so that it can be released later when needed, hence reducing the variability of these energy sources.

Over the past decade, electricity production has increased drastically, and as of 2012, the total annual gross output of electricity was over 22,200 TWh, with fossil fuels such as coal, natural gas, and oil accounting for approximately 70% of the total installation capacity [1]. The load balance has primarily been controlled by fossil fuel power plants in order to preserve the stability of the electricity network. Accordingly, future electricity generation should advance with a decreasing reliance on fossil fuels which are considered finite and environmentally unsustainable [2, 3]. Therefore, exploring renewable energy sources in order to fulfill the goal of reducing CO_2 emissions is the major focus in energy storage technologies. To maintain load balance and assure the stability and dependability of the power network, the majority of renewable energy sources are naturally intermittent [1]. Modern battery technology offers a number of advantages over earlier models, including increased specific energy and energy density (more energy stored per unit of volume or weight), increased lifetime, and improved safety [4]. By installing battery energy storage system, renewable energy can be used more effectively because it is a backup power source, less reliant on the grid, has a smaller carbon footprint, and enjoys long-term financial benefits.

In response to the increased demand for low-carbon transportation, this study examines energy storage options for renewable energy sources such as solar and wind. Energy storage systems (ESSs) are critical components of renewable energy technologies, and they are a growing area of renewed attention. The system requirements, cost, and performance characteristics largely influence the technology of choice [5]. Batteries, hydrogen fuel storage, and flow batteries are examples of electrochemical ESSs for renewable energy sources [6]. Mechanical energy storage systems include pumped hydroelectric energy storage systems (PHES), gravity energy storage systems (GES), compressed air energy storage systems (CAES), and flywheel energy storage systems [5]. Electrical energy storage systems include supercapacitor energy storage systems (SES), superconducting magnetic energy storage systems (SMES), and thermal energy storage systems [5]. Energy storage, on the other hand, can assist in managing peak demand by storing extra energy during off-peak hours and releasing it during periods of high demand [7]. In addition to reducing the need for increased production capacity, this can also help prevent brownouts and blackouts. Grid stability and dependability are critical in supplying backup power during outages and balancing the supply and demand of energy [8]. By enabling small-scale renewable energy sources such as rooftop solar panels to store surplus energy and transfer it back into the grid when necessary, energy storage can support the decentralization of energy generation. Consequently, smart grids can be facilitated to enhance energy independence.

Empowering green energy to reach its full potential is essential in addressing the growing environmental problems the world is facing today as a result of increased pollution occasioned by the use fossil fuels and woody biomass [9]. Electrical energy demand and supply can be balanced through robust energy storage systems (ESS) [10]. Chemical, mechanical, thermal, or magnetic energy storage conversion techniques are viable options for energy storage. Electrical energy can be generated when it is needed and preserved when there is an excess of supply. Due to market deregulation, challenges with power quality, and pressure to reduce carbon dioxide emissions, it has led to increase in energy prices, which conventional energy production technologies are unlikely to respond effectively [11]. Because of their intermittent nature over a variety of timescales, renewable energy sources (RES) along with potential distributed generation (DG) are thought of as supplements or replacements for conventional generation methods [12]. This review therefore highlights various storage energy interventions that are important in energy conservation and which if advanced will enhance clean energy access especially in off-grid systems and remote environments.

In order to address evolving energy demands such as those of electric mobility, energy storage systems are crucial in contemporary smart grids. By utilizing a variety of technologies including electromechanical, chemical, thermal, and electrochemical (batteries), energy storage offers flexibility and potential for remote places [13]. Three basic functions of electrical energy storage (EES) are to reduce the cost of the electricity supply by storing energy during off-peak hours, increase reliability during unplanned outages or disasters, and maintain and enhance power quality in terms of frequency and voltage. Energy storage is essential to ensuring a steady supply of renewable energy to power systems, even when the sun is not shining and when the wind is not blowing [14]. Energy storage technologies can also be used in microgrids for a variety of purposes, including supplying backup power along with balancing energy supply and demand [15]. Various methods of energy storage, such as batteries, flywheels, supercapacitors, and pumped hydro energy storage, are the ultimate focus of this study.

One of the main sustainable development objectives that have the potential to change the world is access to affordable and clean energy. In order to design energy storage devices such as Li-ion batteries and supercapacitors with high energy densities, researchers are currently working on inexpensive carbon electrode materials. Because of their low maintenance needs, supercapacitors are the device of choice for energy storage in renewable energy producing facilities, most importantly in harnessing wind energy. Due to charging and discharging cycles, high power density, low maintenance requirements, extended lifespan, and environmental friendliness, supercapacitors are utilized as robust energy storage devices. In contrast to batteries, supercapacitors are constantly utilized in systems and devices that demand a high power supply because of their remarkable advantages. Supercapacitors are currently used in many fields of interest, including industrial control, power, transportation, consumer electronics products, national defense, communications, medical equipment, and electric and hybrid vehicles, and this is ascribed to their high performance and market penetration potential.

Research on flexible energy storage technologies aligned towards quick development of sophisticated electronic devices has gained remarkable momentum. The energy storage system such as a battery must be versatile, optimized, and endowed with strong electrochemical qualities. The benefits of energy storage, including their size, weight, and environmental focus, make them suitable for a variety of applications [16]. Applications that call for storing and releasing large amounts of energy quickly are driving an increase in the use of energy storage devices. The automotive sector, global hybrid transportation systems, grid stability, electric vehicles, and rail-system power models are examples of current industry applications of renewable energy [17]. An energy storage facility typically consists of a storage medium, a power conversion system, and a system balance. Chemical, electrochemical, mechanical, electrical, and thermal storage technologies can be employed in renewable energy systems [18]. Energy storage is essential for ensuring a steady supply of renewable energy to power systems, even in the absence of the sun and when the wind is not blowing. A way to increase flexibility, improve grid dependability and power quality, as well as allow for the expansion of renewable energy sources is through energy storage such as the one presented in Figure 1.

Energy storage is important because it can be utilized to support the grid's efforts to include additional renewable energy sources [20]. Additionally, energy storage can improve the efficiency of generation facilities and decrease the need for less efficient generating units that would otherwise only run during peak hours. On a positive note, energy storage can lower greenhouse gas emissions as well as air pollution by promoting the production of more renewable energy and eliminating the use of fossil fuels [21]. Moreover, it can facilitate the integration of distribution of mains electricity with off-grid renewable energy sources and increase the stability and resilience of the grid [22]. Energy storage can slow down climate change on a worldwide scale by reducing emissions from fossil fuels, heating, and cooling demands [23]. Energy storage at the local level can incorporate more durable and adaptable energy systems with higher levels of energy security by incorporating locally generated energy. In order to address evolving energy demands, such as those of electric mobility, they are essential in contemporary smart grids [24]. Energy storage uses a variety of methods, notably electromechanical, chemical, thermal, as well as batteries (Table 1), to provide flexibility along with possible applications in remote places [27].

Storage energy density is the energy accumulated per unit volume or mass, and power density is the energy transfer rate per unit volume or mass [28]. When generated energy is not available for a long duration, a high energy density device that can store large amounts of energy is required. When the discharge period is short, as for devices with charge/discharge fluctuations over short periods, a high-power density device is needed. Energy storage systems also can be classified based on the storage period. Short-term energy storage typically involves the storage of energy for hours to days, while long-term storage refers to storage of energy from a few months to a season [29]. Energy storage devices are used in a wide range of industrial applications as either bulk energy storage as well as scattered transient energy buffer. Energy density, power density, lifetime, efficiency, and safety must all be taken into account when choosing an energy storage technology [20]. The most popular alternative today is rechargeable batteries, especially lithium-ion batteries because of their decent cycle life and robust energy density. Their low power density and elevated ESR, which may significantly restrict their capacity to provide power when confronted by large current loads, are their major drawbacks [30]. Therefore, they cannot be deployed in some applications because of these constraints. Moreover, it is noted that high current rate along with transient loading situations reduces battery life. For the purpose of fulfilling pulse and peak power requirements, robust architecture is typically used to make up for these shortcomings which increase the cost of harnessing energy from the storage device.

Numerous technologies, including nickel-metal hydride (NiMH), lithium-ion, lithium polymer, and various other types of rechargeable batteries, are the subject of recent research on energy storage technologies [31, 32]. However, dependable energy storage systems with high energy and power densities are required by modern electronic devices. One such energy storage device that can be created using components from renewable resources is the supercapacitor [33]. Additionally, it is conformably constructed and capable of being tweaked as may be necessary [34]. Nevertheless, the comprehensive and independent use of this technology in commercial products is constrained by its low energy density capacity. In order to supply power more affordably during off-peak hours, a better energy storage system must be developed or be used together with supercapacitors [35]. Supercapacitors, for instance, are energy delivery and storage systems that can store and transfer a high amount of energy in a short period of time [36].

The main focus of energy storage research is to develop new technologies that may fundamentally alter how we store and consume energy while also enhancing the performance, security, and endurance of current energy storage technologies. For this reason, energy density has recently received a lot of attention in battery research. Higher energy density batteries can store more energy in a smaller volume,

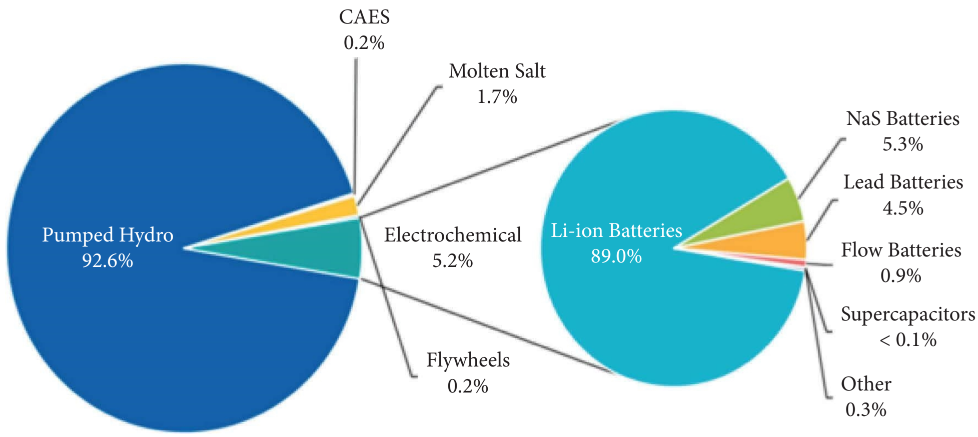

Figure 1: Projected capacity of all operational ESTs worldwide (MW)—adapted from the global energy storage project database of CNESA [19].

Table 1: Technology comparisons between various battery types [25, 26].

Battery type	Advantages	Disadvantages
Flow battery	(i) Independent energy and power rating (ii) Long service life (10,000 cycles) (iii) No degradation for deep charge (iv) Negligible self-discharge	(i) Medium energy (40–70 Wh/kg)
Lithium-ion	(i) High energy density (80–190 Wh/kg) (ii) Very high efficiency 90–100% (iii) Low self-discharge (1–3% per month)	(i) Very high cost ($900–1300 kwh) (ii) Short life cycle due to deep discharge (iii) Require special overcharge protection circuit
Lead acid	(i) Low cost (ii) Low self-discharge (2–5% per month)	(i) Short cycle life (1200–1800 cycles) (ii) Cycle life affected by depth of charge (iii) Low charge density (about 40 Wh/kg)
Nickel based	(i) Can be fully charged (3000 cycles) (ii) High energy density (50–80 Wh/kg)	(i) High cost ten times that of lead acid (ii) High discharge (10% per month)
Sodium Sulphur (NaS)	(i) High efficiency (85–92%) (ii) High energy density (100 Wh/kg) (iii) No degradation for deep discharge	(i) Be heated in stand-by mode at 3250°C

which makes them lighter and more portable. For instance, lithium-ion batteries are appropriate for a wide range of applications such as electric vehicles, where size and weight are critical factors [37]. They offer a far better energy density than conventional lead-acid batteries. Researchers are continuously working to improve the efficiency of current technology in addition to developing new ones. There is therefore an urgent need to explore methods that lessen the energy lost during charging and discharging cycles.

One of the current cutting-edge energy storage technologies is the use of thin-film lithium-ion batteries (LIBs) [38]. LIBs have been shown to be the energy market's top choice due to a number of essential qualities including high energy density, high efficiency, and restricted self-discharge, prolonged life cycle even at high charging and discharge rates. The structure of the electrode material in lithium-ion batteries is a critical component impacting the electrochemical performance as well as the service life of the complete lithium-ion battery. Lithium-ion batteries are a typical and representative energy storage technology in secondary batteries. In order to achieve high charging rate performance, which is often required in electric vehicles (EV), anode design is a key component for future lithium-ion battery (LIB) technology. Graphite is currently the most widely used anode material, with a charge capacity of 372 mAh/g. Additionally, silicon offers an appealing operating voltage and a low discharge potential. There are several energy storage technologies that can offer the power system a range of services and advantages. Pumped hydro, batteries, flywheels, compressed air, thermal storage, as well as hydrogen, are a few of the more popular systems [39, 40]. The capacity, power, efficiency, price, lifespan, and environmental impact of each technology are unique.

A number of technologies may be better suited for a given application than others. For instance, pumped hydro can offer extensive and lengthy storage, but it has substantial upfront costs and demands suitable sites. Figure 2 presents the energy storage characteristics of various energy storage systems. Although batteries have a finite lifespan and degrade over time, they can offer quick and flexible reaction as well as balancing demand and supply, improving grid stability, lowering peak demand, and boosting resilience [20]. In order to mitigate the volatility and unpredictability of renewable energy sources such as wind and solar, there is

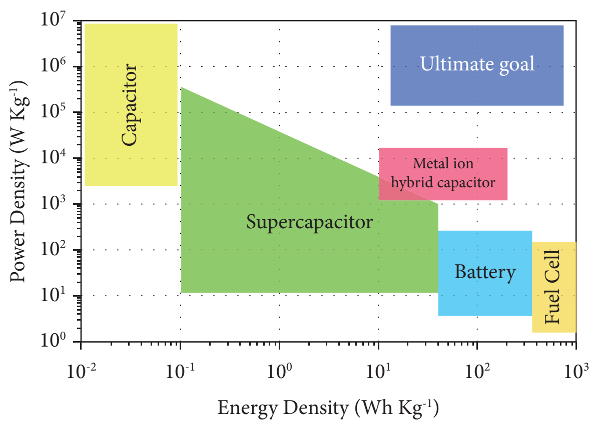

Figure 2: A preview of the contrast in numerous energy storage technologies [41].

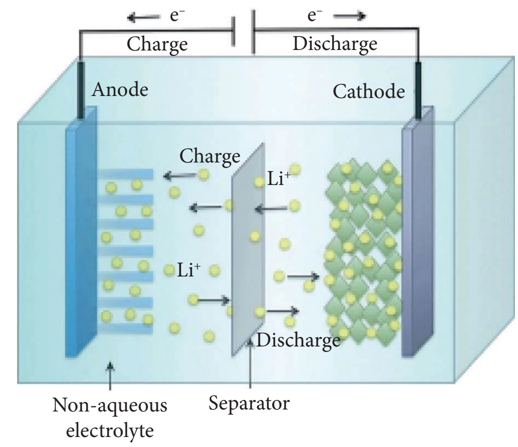

Figure 3: The intercalation of lithium-ions (yellow spheres) into both cathode and anode matrices during charge and discharge cycles [48].

a need to store surplus energy whenever it is available and discharging it when it is required [42, 43]. As an additional benefit, energy storage can offer auxiliary services such as voltage and frequency regulation to uphold the consistency and dependability of the power supply.

Despite its benefits, energy storage continues to encounter a number of drawbacks to widespread adoption, including high costs, shortage of incentives, and technological difficulties [44]. Energy storage systems, nevertheless, might need to be interoperable with various tools, platforms, and protocols as well as the infrastructure and operations of the current grid infrastructure. Due to environmental concerns, clean energy, including its storage, conversion, and use, has received increasing attention [45, 46].

Because of their numerous benefits, including their high energy density, lengthy life cycle, and environmental friendliness, lithium-ion battery (LIBs) have emerged as the most essential power source for electronics including electric cars [47]. The current collector, a central component of LIBs, supports electrode materials and transports electrons from the active material to the external circuit (cf. Figure 3). Aluminum and copper foils are typically employed as the current collectors for the cathode and anode, respectively, to prevent electrochemical corrosion of the current collector [49, 50]. Due to its structural stability as well as minimal electrochemical reactivity in relation to lithium ions, graphite has traditionally been employed as the anode of choice in lithium-ion batteries [51].

However, the current collector has received relatively little attention in LIB technology research, which focuses more on developing cathode materials and electrolytes [52]. The electrical component of LIBs, especially thin-film LIBs, has not been given significant attention, and current collectors have always been thought to be indefinitely conductive [48, 53]. Moreover, the resistance of the current collector has not been individually simulated and is typically included in the overall ohmic resistance and contact resistance. Studies on modeling of thin-film current collectors are scarce in literature. Thin-film LIBs resistance to current collectors could cause abrupt voltage changes and potential differences in batteries, which can lead to polarization and degradation in battery performance. The utilization of materials in batteries as well as the current density distribution can both be impacted by its resistance, which is a subject of continuous research [54]. Therefore, research on the current collector's resistance is necessary. The 2-D Poisson equation for thin film is derived from the traditional 3-D Laplace equation depicting the prediction capability in a flat slab [55, 56]. The 3D-Laplacian equation is given as expression 1, whereas the Poisson equation is given as expression 2.

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial Z^2} = 0, \tag{1}$$

$$\nabla^2 \Phi = \sigma(x). \tag{2}$$

The collector's resistance is suggested to transform and connect the parameters of the 2-D equations (sheet resistance) with the parameters of the 3-D equations (resistivity and geometrical dimensions) [54]. The thin-film's thickness is assumed to be minimal in comparison to other dimensions. The proposed derivations about the thin-film current collector's resistance and the modeling of electronic currents are helpful in enhancing the current thin-film lithium-ion battery models [54]. LiBs have a well-established place in a variety of applications, including energy storage systems, mobile devices, power tools, aircraft, automotive, and maritime transport [7]. LiBs are attractive to both domestic and business because they provide higher energy and power densities than traditional battery technologies such as thermal or mechanical systems. Solid-state lithium batteries are attractive possibilities for energy storage systems because they inspire greater safety and high energy densities [57]. Low power density, which is brought about by elevated resistance at the electrode as well as solid electrolyte interfaces, has unfortunately hindered the development of robust energy storage batteries [58]. For this reason, reducing contact resistance has become a central concern in energy storage research. Although buffer layers have been added between sulfide electrolytes and $LiCoO_2$, the reduction in interface resistance is still insufficient [59, 60]. Despite the importance of designing low-resistance interfaces, interface resistance is yet to be understood and managed. In general, energy density is a crucial aspect of battery development, and scientists are continuously designing new methods and technologies to boost the energy density storage of the current batteries. This will make it possible to develop batteries that are smaller, resilient, and more versatile. This study intends to educate academics on cutting-edge methods and strategies to enhance the energy density of batteries through the approaches and applications described herein. Figure 4 gives a basic layout of a thin-film solid-state energy storage battery.

One technique for understanding how interface resistance arises, specifically how ions travel across solid electrolyte/electrode interfaces, is to use thin-film batteries consisting of epitaxial films [62]. This approach enables a quantitative evaluation of interface resistance by providing clearly described surface areas, atomic structures, and crystal orientations at the contact. The interface resistance of $LiCoO_2/Li_3PO_4$-xNx and $LiNi_{0.5}Mn_{1.5}O_4/Li_3PO_4$ thin-film batteries is extremely low, and they have demonstrated rapid charging abilities. To more effectively study interfacial properties, a flat, positive electrode surface is desirable [63]. It is, nonetheless, challenging to build electrode surfaces that are flatter and more controlled because the bottom electrode (metal current collector), which is inserted between the positive electrodes and substrates, has a rough surface [64]. Thus, it is crucial to deposit highly electronically conducting positive-electrode materials in order to eliminate the bottom current collector. However, current fabrication processes for 3-D nanostructures, including additive manufacturing methods, improved lithography techniques, and other nanopatterning techniques, are intrinsically expensive [65]. Low-cost 3-D printed fiber structures can be made using electrospinning as an integrated additive manufacturing approach.

Figure 5 represents a general explanation of how lithium-ion battery thin-film printing functions. The method of printing the film layers in layers is known as "deposition." In thin-film Li-ion batteries, the components typically deposited corresponding include substrate, cathode current collector, cathode, electrolyte, anode, anode current collector, and protective coating [67, 68]. Despite a decrease in overall power use, renewable energy generation such as that from wind, solar, biofuels, and geothermal energy, etc., is experiencing the fastest growth yet in recent times [35]. The key forces behind this momentous expansion are the significant improvements in the production of both solar and wind energy [69]. The percentage of renewable energy produced globally has soared at the fastest rate ever recorded, and the rise in global power output has largely been attributed to renewable energy sources, with solar and wind generation accounting for the observed increase as can be noted in Figure 6 [70].

2. Operational Principles and Safety of Lithium Batteries

The cathode, anode, separator, and electrolyte make up a lithium-ion cell. The materials for the anode and cathode are, respectively, placed onto copper and aluminum foil current collectors [54]. The separator lies between the anode and the cathode to avoid shorting between the two electrodes while still allowing ion transfer [71]. The electrolyte facilitates the flow of lithium ions between the electrodes. Lithium ions travel from the anode and intercalate into the spaces between the layers of cathode crystals during the discharge reaction [72]. Lithium ions migrate from the positive side of the battery's cathode and insert into the anode during charging. Solid-electrolyte interphase (SEI), which is a passivation layer on the anode that is passable to lithium ions but not to the electrolyte, is formed when intercalated lithium ions react rapidly with the solvent of the electrolyte during the initial charging cycle. The safety and well-being of LiBs depend on the SEI's stability.

Because of its substantial specific energy and elevated voltage, lithium-ion batteries (LIBs) have taken over as the primary power sources for portable gadgets and electric vehicles since their commercialization in the late 1990s [73]. Nonetheless, in recent years, due to the widespread promotion and use of LIBs, numerous safety incidents caused by thermal runaway (TR) have occurred worldwide, raising serious concerns about LIBs, particularly in grid-scale energy storage [73]. The reaction can be separated into early, medium, and late stages depending on the time-sequence of TR. First, because electrolyte combustion contributes a significant amount of heat in the late stages of TR, it makes sense and is a standard practice to switch to nonflammable electrolytes such as solid-state electrolytes, flame retardant electrolytes, or aqueous electrolytes. Secondly, the primary middle-stage method concentrates on enhancing thermal stability and reducing separator shrinking. Third, at the intermediate stage of TR, the self-heating rate is accelerated by heat-accumulating reactions involving the charged cathode and electrolytes. In order to prevent oxygen escape and provide a stable cathode-electrolyte contact, surface coating and an all-fluorinated electrolyte are selected [74]. Following ionization and passage through the electrolyte, Li ions travel from the anode to the cathode during discharge [75]. Li ions undergo an oxidation state transition at the positive electrode. This mechanism is entirely reversible during charging. Li ions can pass through the tiny holes of the micropermeable separator [76] as can be observed in Figure 7.

2.1. The Science of Thin-Film Batteries.

The anode, cathode, current collector, substrate, electrolyte, and a separator make up a thin-film Li-ion battery. It is observed that, in contrast to traditional LiBs, the substrate plus current collector is required [72]. The foundation layer in the deposition process is a thin ceramic layer known as a substrate. The conducting route between the electrodes as well as the battery's external electronics is provided by the current collector, which is

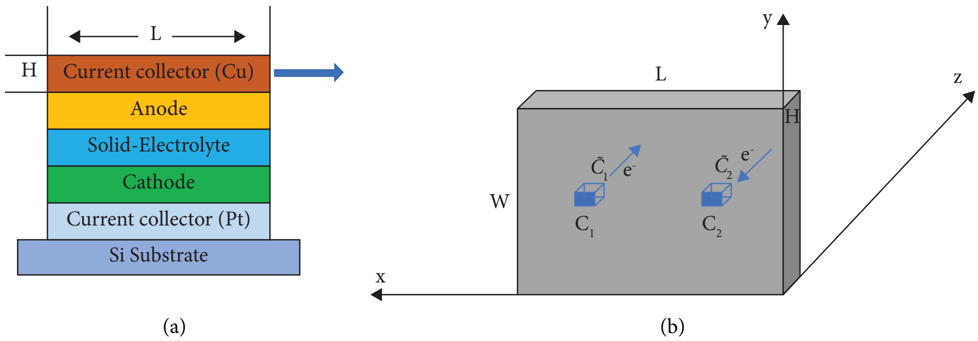

FIGURE 4: Thin-film solid-state battery (a) while (b) is the layout for the current collector's distribution. The direction of the electrons is indicated by the blue arrows [61].

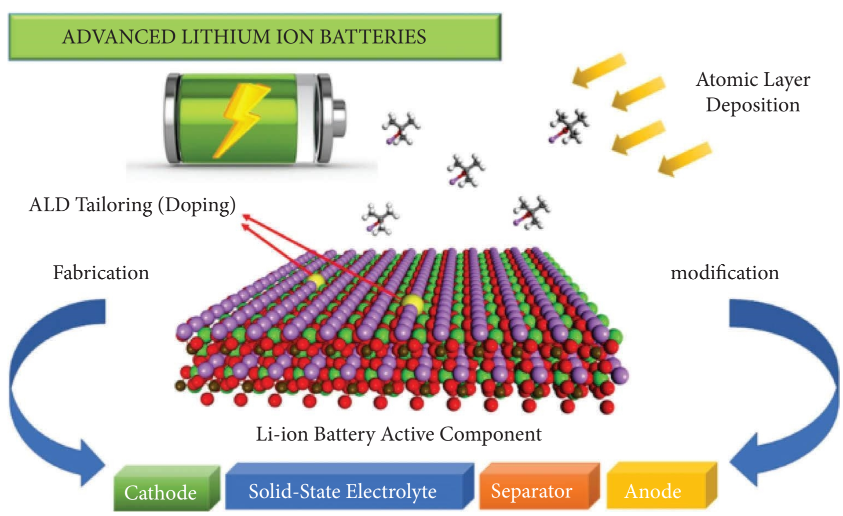

FIGURE 5: Deposition of thin-film Li-ion batteries on a substrate during manufacture [66].

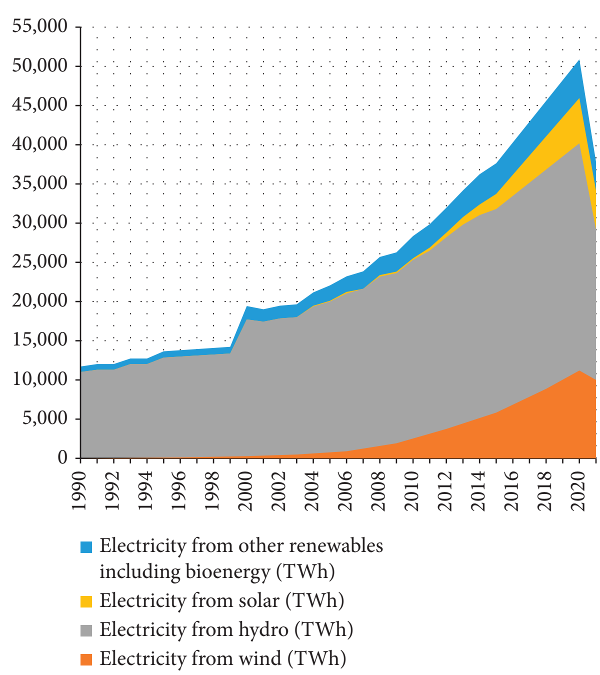

FIGURE 6: Global transition to the production of renewable energy [35].

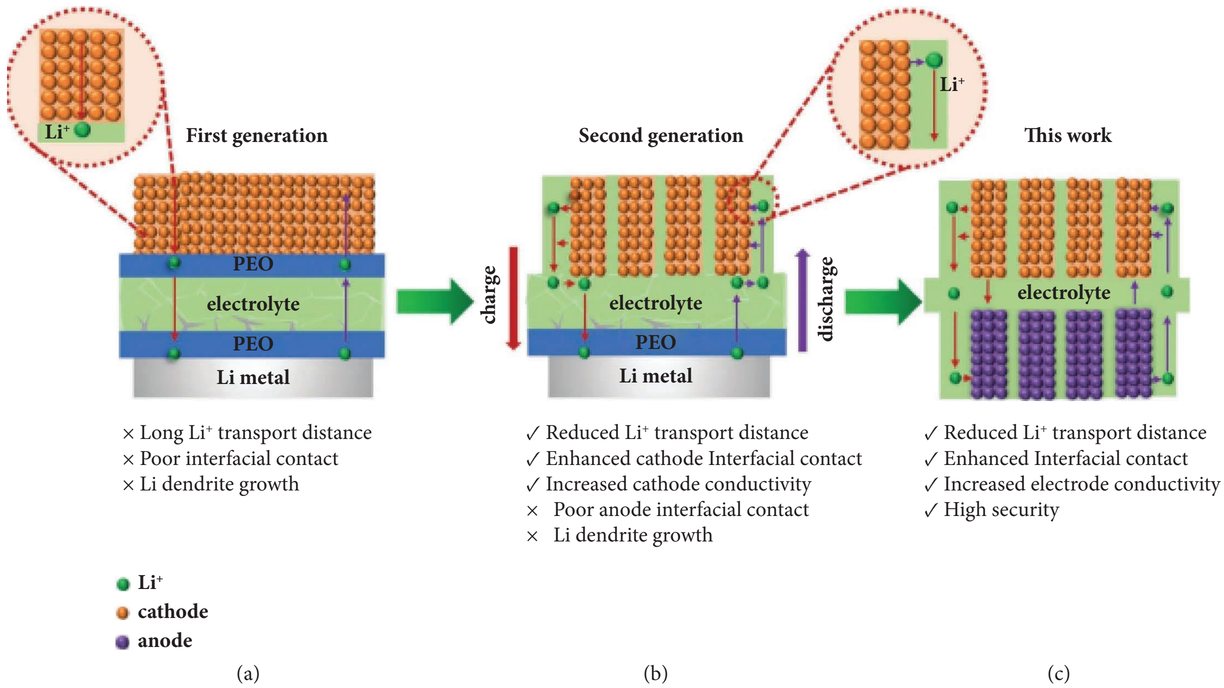

FIGURE 7: (a) All-solid-state lithium-ion battery development. (b) The manufacturing process for the second-generation battery and (c) the three-layer, all-ceramic 3D vertically aligned microchannel battery [77].

a thin sheet of metal [78], whereas the main layers in the creation of thin-film batteries are the current collector layer, anode layer, electrolyte layer, cathode layer, and another collector layer. Thin-film printing technology is a sophisticated chemical-physical procedure frequently utilized in the fabrication of optics as well as semiconductor devices. The current collectors, which typically comprised silver nanowires and carbon nanotubes (CNT), are placed on top of the substrate [9]. There are several methods for depositing cathode materials, but the two most used ones are pulsed laser deposition (PLD) and chemical vapor deposition (CVD) techniques. Solid polymer-based electrolyte materials are utilized in thin-film lithium-ion batteries, and they are coated on top of the cathode material using the magnetron sputtering technique [79, 80]. Solid-polymer electrolytes have the benefit of serving as both an electrolyte and a separator [81].

2.2. Uses of Lithium Ion. From electronics to toys, wireless headphones, handheld power tools, small and big appliances, electric cars, electrical energy storage system laptops and smart phones to solar and wind farms, energy storage, are just a few of the devices that employ LiBs, and has therefore become a critical component of modern life [82]. The electrification of electric vehicles is the newest application of energy storage in lithium ions in the 21st century. In spite of the wide range of capacities and shapes that energy storage systems and technologies can take, LiBs have shown to be the market's top choice because of a number of remarkable characteristics such as high energy density, high efficiency, restricted amount of self-discharge, and longer life cycle even at high charging and discharging rates. Nonetheless, the key advantages of lithium-based batteries include (i) lightweight (50–60% less weight than lead acid) equivalent, (ii) longer lifetime, (iii) more useable capacity, (iv) constant power, (v) temperature tolerant, and (v) fast charging and safety.

On the other hand, there are inherent drawbacks because they require a protective circuit to function optimally because of their sensitive nature [83]. Moreover, each pack has a protective circuit that regulates the maximum charging voltage that each cell can achieve and keeps the voltage from dropping too low during discharge, which causes high strain and delamination from the current collector, which may result in electrode failure. According to Figure 8, the electrical resistance related to current collection comprises contributions from the electrode, the current collector (CC), and the contact interface between these elements [85, 86]. To optimize the design of efficient CCs, aiming to minimize both the total resistive power loss factor, P^*, and the mass of the current collector, mcc, design engineers need to carefully select values for various parameters [87]. These include the thickness of the CC (tcc), its area fraction (Af), calculated as Acc/Acell, where Acc and Acell represent the geometric areas of the CC and the cell, respectively, and the bulk electrical conductivity of the CC material (σcc). Additionally, factors such as the bulk electrical conductivity of the electrode (σe), the contact conductivity of the electrode/CC interface (σC), the current density (js), the length of the cell (Lcell), and its area (Acell) also influence the design process [88].

2.3. In-Built Quasi-Solid-State Poly-Ether Electrolytes in Li-Metal Batteries. Solid-state lithium metal batteries (SSLMBs) have a promising future in high energy density

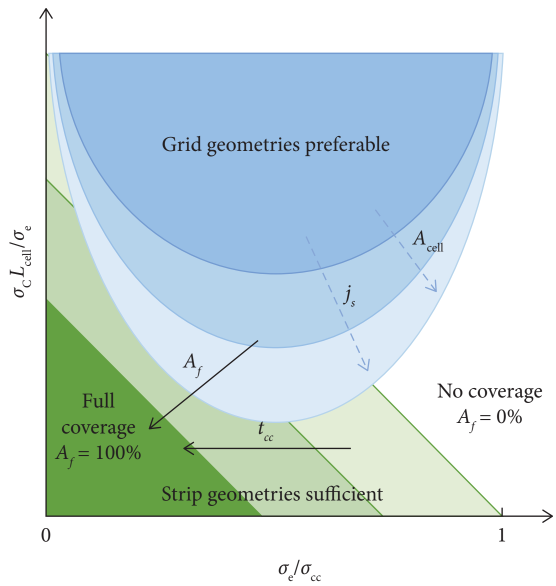

Figure 8: The design possibilities for current collectors depicting the range of parameters where strip (green) or grid (blue) configurations are favored. Here, the solid arrows signify optimal parameter choices, while dashed arrows represent the influence of parameters on the extent of design options [84].

and extremely safe energy storage systems because of their dependable electrochemical stability, inherent safety, and superior abuse tolerance [84]. The constant explosion of materials and chemistry has given rise to numerous solid-state electrolytes (SSEs). Practical uses of solid-state metal batteries (SSMBs) depend on the development of solid-state electrolytes that are compatible with high-voltage cathodes and stable battery operation over a wide temperature range [89]. To obtain highly stable performance in terms of electrochemistry and thermodynamics, a solid eutectic electrolyte is used on the cathode surface [74]. This performance is primarily attributable to enhanced interface stability and superb-cyclic stability in Li||Li symmetric batteries, as well as better compatibility at the electrode/electrolyte interface brought about by nanohierarchical solid polyether electrolytes (SPEE) [84]. In situ SPEEs, formed in the process of upgrading electrochemical cells employing conventional ether-based electrolytes such as 1,3-dioxolane (DOL), through cationic ring-opening polymerization reaction are an effective and easily industrialized method for achieving intimate interface contact and compatibility with metallic lithium [90].

3. Compressed Air Energy Storage

By compressing air within an air reservoir utilizing a compressor supplied with off-peak and cheap electric energy system, compressed air energy storage (CAES) systems can store energy [91]. A desirable energy storage method for large-scale bulk storage is CAES. The power plant's generator runs backwards like a motor during charging to inject the reservoir with compressed air. The compressed air is used to run a combustion turbine generator at the plant's discharge. Similar to a traditional turbine plant, natural gas is burnt during plant discharge [92, 93]. However, a CAES plant's combustion turbine utilizes every bit of its mechanical energy to produce electricity during discharge, and as a result, the system is more effective. There are several potential reservoir types where compressed air can be kept in naturally existing aquifers (like traditional natural gas storage), in rock compartments that have been artificially built. Storage in aquifers is by far the most prevalent and least expensive type of energy storage technologies which has so far been advanced.

4. Superconducting Magnetic Energy Storage Devices

Superconducting magnetic energy storage systems (SMES) are one of the best storage technologies. They store energy in a magnetic field produced when direct current is run through a superconducting coil; since the coil cools below its superconducting critical temperature, the system suffers almost no resistive loss [94]. Magnetic fields are used as a form of energy storage in SMES. Superconducting components are used in the system to transform the input energy into magnetic fields. A typical SMES is made up of four parts: a superconducting coil magnet (SCM), a power conditioning system (PCS), a cryogenic system (CS), and a control unit (CU). In superconducting magnetic energy storage (SMES) devices, the magnetic field created by current flowing through a superconducting coil serves as a storage medium for energy. The superconducting coil's absence of resistive losses and the low level of losses in the solid-state power conditioning contribute to the system's efficiency. SMES offer a quick response for charge or discharge, in a way an energy battery operates. In contrast to a battery, the energy available is unaffected by the rate of discharge.

Large forces are applied to the conductor as a result of the magnetic field's interaction with the circulating current. The conductor itself may readily carry these forces in a small magnet [95]. To carry these loads in much bigger magnets, a support structure must be supplied, either inside the coil windings or outside the coil. Modern SMES devices use coil windings which are made of a standard metallic superconducting material (Nb-Ti or Nb3Sn) that is cooled by liquid helium [96, 97]. Currently, the power leads that link the coil to the ambient temperature power conditioning system use extreme temperature ceramic superconductors cooled by liquid nitrogen [94, 98]. An electrically conducting coil experiences direct current (DC), which creates a magnetic field that keeps the current flowing. SMES utilizes a superconducting material instead of the iron and copper coils often used in everyday applications such as transformers. Such a coil minimizes all resistive losses because its electrical resistance is nearly zero. Figure 9 presents the operational assembly of SMES.

The price of refrigeration and the quality of the superconducting coil are the main drawbacks of SMES [100]. Although work is being done to develop high-temperature superconductor (HTSC) technology, which does not require extremely low temperatures and uses inexpensive liquid

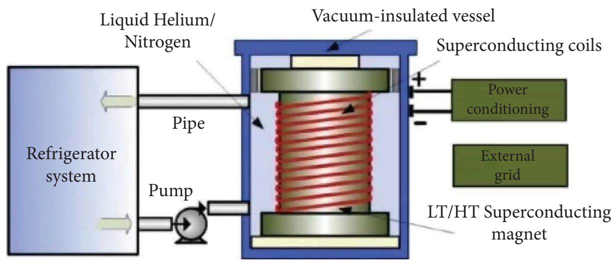

Figure 9: The SMES operating assembly [99].

nitrogen instead of the expensive liquid hydrogen or liquid helium needed for a very low-temperature superconductor, the price of HTSC material continues to be unaffordable. Huge coils, some of which have a diameter of several hundred meters, are required for SMES with a huge capacity of 5–10 GWh [101], which ultimately adds into the system's cost. SMES represents a high-power technology that offers greater power density over other devices for comparable tasks, but it is also costly, has a low energy density, and suffers from significant parasitic energy losses. The high cooling demands, sensitivity to magnetic field conditions, current strength, and magnetic field variations are the system constraints.

4.1. Supercapacitors. Supercapacitors, a new generation of technology, have the potential to significantly increase energy storage [102]. Although supercapacitors and regular capacitors have the same fundamental principle, supercapacitors have a better efficiency than regular capacitors because of the electrode's bigger surface area and less thick dielectrics [103]. Conventional capacitors store energy in the electric charge created between two conducting plates [104]. The size of the plates, how far apart they are from one another, as well as the type of material being used as the dielectric all affect the capacitance of the supercapacitor. By switching the voltage direction, energy is released. The term "supercapacitor" refers to the energy density of direct current (DC) that has undergone orders of magnitude improvement as a result of cutting-edge electrode material selection and manufacturing [105]. Supercapacitors vary from conventional dielectric capacitors in that they store energy in a layer of polarized liquid at the junction of a conducting electrode and an ionic electrolyte [106]. Since the electrode's surface area and capacitance are inversely related, using extremely porous material increases the electrode's surface area. One of the supercapacitor's benefits is its extremely high efficiency and quick-charging capability. Supercapacitor lasts longer than a battery that lasts 10 to 15 years. Whereas a battery can tolerate temperatures between −10 and 40°C, a supercapacitor can withstand temperatures between −30 and 65°C [107]. Supercapacitors can be installed in a tiny space because of how much smaller they are and how supercapacitor responds transiently and rapidly. Since the amount of solar energy received is thought to be significantly greater than the amount needed to support human consumption, it is thought to be a competitive alternative to other renewable energy sources [108, 109].

Due to the inevitable depletion of natural resources and fossil fuels in the long run, solar energy is touted the next frontier for sustainable energy security. Supercapacitor and dye-sensitized solar cells (DSSCs) have the potential to produce electricity continuously [110]. The development of hybridized dye-sensitized solar cell (DSSC) capacitors and DSSC supercapacitors is essential for energy storage operations, and technological advancements have led to the development of a photo-supercapacitor for effective energy harvesting and appropriate storage methods [110, 111]. The idea to combine DSSCs and supercapacitors for efficient energy conversion and storage came about when dye molecules absorbed radiant energy and converted it into electrical energy [112]. The conversion efficiency of a photo-supercapacitor depends on the use of its active components. The performance of the photo-supercapacitor's active elements such as the dye, electrolyte, photo-anode, as well as counter electrode, is what primarily affects how well energy is converted to lengthen storage life [110, 113]. Figure 10 illustrates the processes involved for supercapacitor powered electric motor vehicle.

Electric double layer (EDLC) capacitors or supercapacitors are recommended for use because they can be more easily integrated with battery innovation that can be used in electric vehicles along with other electronic devices as well as their exceptionally high specific power, quick charging, and low ESR. To make it easier to construct better applications and more efficient energy storage technologies and devices, the supercapacitor requires a highly accurate and precise characterization. Because of its appealing qualities including as high power density and high recyclability, supercapacitors, also referred to as EDLCs, are the subject of intensive research and are widely regarded as potential energy storage solutions to the current world energy demand. Although possessing an inadequate energy density, they have advantages including minimal internal resistance, a broad operating temperature range, and remarkable performance. These advantages make them especially well-suited for use in consumer electronic applications, either on their own or in combination with other high-energy devices such as LiBs. A management system that is enabling must be put in place to ensure the successful operation of supercapacitor systems in a way that is also secure and dependable. One of its most significant operations is thought to be the management of cell equalization. Other activities that need systems and control engineering include thermal or temperature management, power system management, safety visualization, and other related functions [115]. Accurate state estimation also offers information on how to improve power regulation and decrease cell nonuniformity in supercapacitor systems.

4.2. Supercapacitors with an Electrolyte-Based Design. A supercapacitor uses a variety of electrolytes, including organic, aqueous, and ionic liquids. These electrolytes are herein discussed.

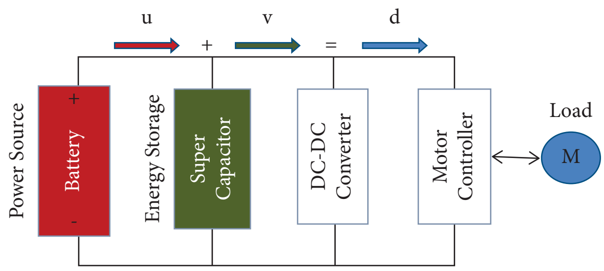

Figure 10: An illustration of a hybrid electric vehicle motor powered by energy storage systems [114].

4.2.1. Nickel Lanthanum Telluride Microfibers for Redox Additive Electrolyte-Based Flexible Solid-State Hybrid Supercapacitor. Flexible, lightweight, and very efficient energy storage technologies are being advanced in response to the growing need for portable and wearable flexible electronics, including foldable cellphones, electronic papers, and implantable medical devices [116]. As a result, achieving high energy and power densities is now essential. In order to advance wearable energy devices, hybrid supercapacitors (HSCs), with their robust power density as well as cyclic stability, have been considered to be a key class of energy storage devices. HSCs use alkaline or acidic liquid electrolytes, which are principally heavy, corrosive, and potentially leaky, and are noted for specialized encapsulating technology that drives up the cost of the device. They comprise one battery-type electrode together with capacitive electrodes. Solid-state electrolytes, which offer additional benefits such as foldability, stretchability, and adhering to the electrode surface, are currently preferred by device manufacturers over their liquid counterparts in order to address inherent technological challenges.

Because of their exceptional mechanical stability, low weight, compact size, and ease of maintenance in today to day applications, flexible solid-state hybrid supercapacitors (FSSHSC) have received significant attention in recent years. However, FSSHSCs are constantly one step behind liquid-state supercapacitors in terms of performance. While it is limited to interacting with the electrode's surface when using gel electrolytes, the wettability of the electrode is greater when using liquid electrolytes [114]. In any event, the energy storage capacity of the solid electrolyte also increases noticeably if it can match the diffusive properties of the liquid electrolyte. Due to their characteristic capacity to enter an electrode's channels like liquid electrolytes, gel polymer electrolytes are a desirable replacement in this situation. Furthermore, they have the same level of conductivity as liquid electrolytes coupled with considerable flexibility, guaranteeing that they offer the advantages of both their solid as well as liquid counterparts [117].

4.2.2. All-In-One Flexible Supercapacitor Based on Chemically Cross-Linked Hydrogel Electrolyte. Flexible and lightweight energy storage systems are necessary for portable electronics [118]. Flexible supercapacitors are one of the several flexible energy storage technologies that have received remarkable attention because they can operate while being bent, folded, or even twisted without experiencing performance deterioration. The performance of flexible supercapacitors is largely influenced by the electrolyte's ionic conductivity and potential window. Gel polymer electrolyte (GPE), which has a high ionic conductivity (10^4 to 10^{-1} Scm^{-1}) while preserving dimensional stability, is thought to be more promising and has inspired the future of energy storage technology [119]. On the other hand, polyvinyl alcohol (PVA) has received the most attention among the different types of polymer matrix for GPE because it is inexpensive, nontoxic, electrically and chemically inert, and chemically stable. In order to create hydrogels, which are three-dimensional, polymeric networks that retain water in a polymer matrix with surface tension, acids (H_2SO_4 and H_3PO_4), alkalis (KOH), or inorganic salts (KCl and Li_2SO_4) are added to PVA substrate in order to get the appropriate ionic conductivity [119]. These PVA-based hydrogel electrolytes are made primarily through a straightforward mixing and physical cross-linking method. Hydrogen bonding, where microcrystallite areas serve as physical crosslink points, stabilizes the hydrogel network of physically cross-linked PVA systems [120].

4.2.3. Flexible, Redox-Active, Asymmetric Supercapacitor Based on Keratin-Derived Renewable Carbon. The design of high energy density flexible devices using two active electrode materials keratin-based renewable resource hierarchically porous carbon as well as hydrous ruthenium oxide (RuO_2) exploits the benefit of asymmetric configuration over symmetric supercapacitors [121]. The device is asymmetrical and has a remarkably high capacitance. However, for devices having a Faradaic energy storage contribution via redox charge transfer mechanism, conventional determination of energy storage characteristics cannot be used. Electrode materials primarily use non-Faradaic (capacitive) along with Faradaic (charge transfer) mechanisms to carry out the charge storage operations [122]. A steady electrochemical working potential window for resistance-free ion mobility is also provided by electrolytes. By utilizing both non-Faradaic and Faradaic charge storage methods, an asymmetric supercapacitor design made up of two different electrode materials can perform much better [123]. The integration of two distinct electrodes in this arrangement provides a broad potential window and ultimately increases the energy density. The electrode specifically takes advantage of the varied oxidation states that redox-active species in carbon materials offer for pseudocapacitance or energy storage through charge transfer and increase electrode wettability [121].

Furthermore, using nanostructured electrodes ensures increased specific surface area, and introducing flaws enables improved electrolyte transport to increase charge/discharge reversibility. Such robust features of the electrode material are taken advantage of by the asymmetric counter electrode used in aqueous electrolyte-based supercapacitor electrode, which increases the working potential above 1.23 V [121]. The device receives large energy density which is attributed to the wide working potential of the supercapacitor. In the current investigation, nanostructured RuO_2 is utilized as a positive electrode because it offers a sizable surface area for ion adsorption during capacitive charge storage. High specific capacitance, enhanced rate capability, a broad operating potential, and electrochemical stability are all products of quick proton transfer. Nonetheless, its limited availability and high cost prevent it from being used extensively. Various methods have been used to reduce the RuO_2 loading in this regard, including (a) using a single electrode in an asymmetric supercapacitor configuration and (b) combining RuO_2 with other electrode materials to create a composite. These methods can improve the performance of supercapacitors while effectively addressing the cost component.

4.2.4. Photo-Supercapacitor. A device used for energy storage referred to as a photo-supercapacitor is made up of dye-sensitized solar cells (DSSCs) which is a key electron contributor that moves the dye electron up to an excited state in the semiconductor's conduction band and a supercapacitor [110]. In the photo-supercapacitor system, DSSCs absorb solar radiation through dye molecules and transform it into electrical energy that may be used to power the supercapacitor charging process [124]. A sensitizer, a photoactive metal oxide deposited on a transparent photo-anode substrate, a counter electrode, as well as an electrolyte, makes up a DSSC device [110]. The photo-anode separates and transfers the photo-generated electrons from the dye sensitizer to the collecting electrode [125]. Numerous metal oxides, including titanium dioxide (TiO_2), tin (IV) oxide (SnO_2), zinc peroxide (ZnO_2), and niobium (V) oxide (Nb_2O_5), serve as photo-anodes for effective photo-anode materials' exploration [110]. Faster electronic transmission, a large specific surface area, and less interfacial electron recombination are all desirable characteristics for photo-anodes used in DSSCs [110].

The supercapacitor's electrode composition determines how much charge can be stored, and consequently, how capacitive the finished product will be. Effective surface area with electrical conductivity is still an important factor in producing high capacitance [121]. The particular characteristics of the materials and the functionality of the components in the working conditions determine how well a device performs. For instance, the electrode material used in the production of high-performance supercapacitors should have a large specific surface area, high electrical conductivity, and robust electrical and thermal stability [126]. By storing the charge at the material's surface via electrical double layer capacitance, carbon materials are suggested as the electrode material [127]. The device's capacitance is enhanced by its high surface area, suitable pore size, pore size dispersion, and presence of functional groups. Graphite, graphene, carbon nanotubes, and activated carbon are examples of commonly used carbon-based materials of interest. Metal oxides, conducting polymers, metal-organic frameworks, MXenes, black phosphorus, and metal nitrides are still important materials [128].

4.2.5. Electric Double Layer Capacitors. The concept of electrical double layer (EDL) in electrochemistry is critical for energy storage, electrocatalysis, as well as a variety of other technological applications, and has undergone significant theoretical modeling advancement over time [129]. However, there are still significant challenges in understanding the minute particulars of the electrochemical interfaces and charging mechanisms under practical conditions. Electric double layer capacitors (EDLCs), often known as supercapacitors, have attracted more attention in recent years, both for their basics and for their uses [130]. A variety of engineering techniques have been advanced in order to improve the device's efficiency with respect to both the energy and power densities [131]. The performance of a supercapacitor is dependent on both the composition of the electrolyte and the electrode pore structure because the characteristics of EDL are sensitive to ion distributions in the vicinity of the electrode surfaces [129]. By employing a coarse-grained framework to simulate the microscopic structure of the porous electrodes along with room-temperature ionic liquids, the effects of polar additions on EDLC capacitance using the classical density functional theory (DFT) are explored [132]. According to the theoretical findings, a highly polar, low-molecular-weight addition has the ability to significantly enhance EDLC capacitance at low bulk concentration. Amorphous electrode materials perform better, and this is ascribed to the additive's ability to reduce the oscillatory dependency of capacitance on pore size [133]. Figure 11 shows a general representation of a capacitor.

EDLCs, also referred to as a supercapacitors or ultracapacitors, function as energy storage devices by creating a double layer of ions at the interface between a porous electrode and an electrolyte [133, 135]. Unlike conventional capacitors, which store energy through charge accumulation on electrode surfaces, EDLCs leverage the electrochemical double layer phenomenon to achieve high capacitance levels. Carbon materials such as graphene, graphene oxides, and carbon nanotubes are utilized as electrode materials in the production of EDLCs [136]. Supercapacitors have attracted considerable attention in recent years because of their distinctive combination of attributes such as high power density, extended cycle life, ecofriendly characteristics, and affordability. Nonetheless, a primary obstacle facing supercapacitors is their relatively modest energy density when compared to alternative energy storage technologies such as batteries. The electrical and electrochemical characteristics of electrode materials play a crucial role in determining their overall effectiveness.

In a typical EDLC energy storage setup, two electrodes are positioned apart and immersed in an electrolyte solution [137]. These electrodes, usually constructed from activated carbon, facilitate a large surface area for ion adsorption. The electrolyte serves as a conductive medium enabling ion movement between the electrodes. Common electrolytes include aqueous solutions like sulphuric acid or organic solvents with dissolved salts [138]. During the charging process, ions from the electrolyte accumulate on the electrode surfaces, forming the double layer. This process is

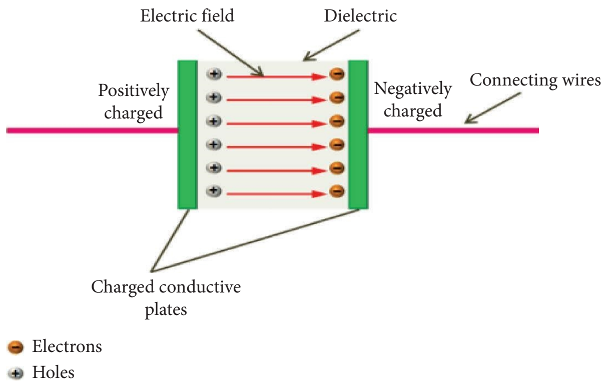

Figure 11: A schematic representation of a general supercapacitor [134].

reversible, enabling the capacitor to efficiently store and release electrical energy. The large electrode surface area and thin double layer contribute to the high capacitance value characteristic of EDLCs, allowing them to store substantial energy per unit volume or weight [139].

One notable advantage of EDLCs is their ability to charge and discharge rapidly, making them suitable for applications requiring high power output or frequent cycling [140]. Moreover, they boast a longer cycle life compared to batteries due to their purely physical energy storage mechanism, enduring hundreds of thousands to millions of charge-discharge cycles with minimal degradation. EDLCs find applications across various sectors, including automotive regenerative braking systems, renewable energy such as smoothing out fluctuations in solar or wind power, consumer electronics like energy backup for smartphones, and industrial applications such as providing burst power for heavy machinery. While EDLCs offer advantages such as high power density, fast charging/discharging, long cycle life, and reliability, they typically exhibit lower energy density compared to batteries [141]. As a result, they are often used alongside other energy storage technologies to complement their strengths in applications where rapid energy storage and release are critical.

4.3. The Use of DFT in Investigating Supercapacitors. Density functional theory (DFT) represents a transformative breakthrough in computational chemistry, simplifying the complexities of quantum mechanics by emphasizing electron density over individual electron behaviors [142]. This methodology streamlines calculations, facilitating predictions of molecular properties such as structure and reactivity by minimizing the energy associated with electron distribution. Comparable to sculpting an electron cloud for stability, DFT efficiency renders it indispensable for analyzing intricate and extensive systems, propelling progress in energy storage designs, catalyst development, and material science [143, 144]. While DFT entails approximations compared to more rigorous quantum mechanics, its computational efficiency enables its widespread application across various scientific domains [145]. Its adaptability spans from unraveling biological processes to engineering innovative technologies, albeit necessitating expert guidance for appropriate approximation selection and interpretation of results [146]. Nonetheless, DFT fundamental role in elucidating electron dynamics within molecules underscores its pivotal contribution to advancing chemistry, material science, and energy storage devices.

The DFT has emerged as a valuable approach for investigating capacitor properties and offering a powerful method for evaluating potential electrode materials for supercapacitors (SCs). Energy density signifies the quantity of energy that can be stored per unit volume or mass of the storage device [147]. In the instance of supercapacitors, although they excel in terms of power density, their energy density typically falls short in comparison to batteries. This drawback stems from the fundamental operational principles of supercapacitors, which involve storing energy through the physical segregation of charges at the interface of the electrode and electrolyte, rather than via chemical reactions as seen in batteries.

To tackle the challenge of low energy density in supercapacitors, researchers are investigating various approaches and the focus lies on developing novel electrode materials with higher specific capacitance, a measure of the amount of charge that can be stored per unit mass or volume. This entails exploring innovative carbon-based materials like graphene, carbon nanotubes, and activated carbon, as well as transition metal oxides and conducting polymers [148]. By nanostructuring electrode materials, researchers can augment their surface area, thereby enhancing the electrode-electrolyte interface and improving charge storage capacity [149]. Techniques such as atomic layer deposition, hydrothermal synthesis, and electrospinning are employed for fabricating nanostructured electrodes [150]. The selection of electrolyte significantly impacts supercapacitor performance. Research endeavors are focused on developing advanced electrolytes with high ionic conductivity, wide electrochemical stability windows, and compatibility with a broad range of electrode materials.

Integrating supercapacitors with other energy storage technologies, such as batteries or fuel cells, in hybrid energy storage systems can harness the strengths of each technology to overcome their respective limitations. This strategy aims to achieve higher overall energy density while maintaining high power capabilities. Innovative device architectures, such as asymmetric supercapacitors and three-dimensional electrode structures, can enhance energy density by maximizing the utilization of available surface area and improving ion diffusion kinetics within the device. Introducing dopants or employing surface functionalization techniques can tailor the electronic and chemical properties of electrode materials, resulting in enhanced charge storage mechanisms and improved energy density [151].

In summary, addressing the challenge of low energy density in supercapacitors necessitates a multidisciplinary approach involving material science, electrochemistry, and device engineering. Continued research and development endeavors in these domains hold the potential to unleash the full capabilities of supercapacitors for diverse practical applications, including electric vehicles, renewable energy systems, and portable electronics.

4.4. Optimizing Supercapacitor Efficiency via Efficient Cell Balancing Management. Supercapacitors have emerged as a leading choice for storing energy, thanks to their impressive features like high power density, fast charging, and long lifespan [152]. However, voltage imbalances among individual cells can significantly undermine their effectiveness, leading to reduced capacity, faster degradation, and safety risks [153]. To address these challenges and maximize the performance, durability, and safety of supercapacitor-based energy storage systems, effective cell balancing management is crucial. Several key factors need to be considered in this regard.

First, the selection of balancing methods is critical. Passive balancing, which redistributes excess energy using components such as resistors, is cost-effective but slower and less efficient, especially for larger setups [154]. Active balancing, which uses electronic circuits for energy transfer, is faster and more efficient but comes with increased complexity and cost. Hybrid balancing, combining passive and active techniques, offers a balance between cost, efficiency, and speed. Secondly, choosing the right balancing algorithms is important. While voltage-based balancing is simple and commonly used, it may not always be the most effective. The mechanism that considers the state-of-charge (SOC) balancing and voltage provides more accurate balancing but requires advanced estimation techniques. Adaptive balancing, which adjusts strategies based on real-time conditions, offers further optimization potential.

Moreover, design considerations are crucial. The number of balancing circuits depends on factors like the number of cells, desired balancing speed, and budget. Balancing speed is essential, as faster balancing improves performance but increases complexity and cost [155]. Energy efficiency is also vital to minimize consumption and maintain overall system efficiency [156]. Moreover, factors such as supercapacitor characteristics and specific system requirements should be taken into account. Different supercapacitor types may require different balancing approaches, and the balancing strategy should align with the application's power and energy needs [157].

In summary, efficient cell balancing management is essential for unlocking the full potential of supercapacitor-based energy storage systems, ensuring optimal performance, longevity, and safety. By carefully considering balancing methods, algorithms, design aspects, and other factors, engineers can develop robust and tailored energy storage solutions for various applications.

5. Aqueous Rechargeable Batteries Based on Organic-Aluminum Coupling

By encouraging the flow of ions from the cathode to the anode during charging and in the opposite direction during discharging, the electrolyte acts as a catalyst to ensure that the battery is conductive [158]. Ions are electron-gained or electron-lost in electrically charged atoms. Soluble salts, acids, and other bases in liquid, gelled, or dry forms make up the electrolyte of a battery [159]. Additionally, the electrolyte is available in solid ceramic, polymer (used in solid-state batteries), and molten salt (used in sodium-sulphur-based batteries) [160]. Aqueous aluminum batteries, with their abundant supply of raw materials, affordability, safety, and high theoretical capacity, are a promising alternative to lithium batteries for commercial energy storage applications. Because of the abundance of aluminum in the earth's crust, its low cost, and its higher potential volumetric energy density than lithium-ion batteries, aqueous rechargeable batteries have attracted significant attention from researchers [161]. A type of rechargeable battery called aluminum-ion batteries uses aluminum ions as charge carriers [162]. Each ion of aluminum can exchange three electrons. This indicates that three Li^+ ions are inserted for every one Al^{3+} ion [163]. This battery's trivalent charge carrier, Al^{3+}, is both a benefit as well as a drawback. Although the energy storage capacity is greatly increased by transferring three units of charge by a single ion, the electrostatic intercalation of the electrodes with a trivalent cation is too powerful for clearly defined electrochemical behavior [164]. Theoretically, Al-ion batteries have a volumetric capacity of 8040 mAh/g and a gravimetric capacity of 2980 mAh/g when Al dissolves to Al^{3+} [165]. High capacity, low cost, and minimal flammability are all possible with rechargeable aluminum-based batteries [166]. The inertness of aluminum and its simplicity to handle in a natural setting has the potential to significantly increase safety. Consequently, aluminum batteries may end up being smaller in future Al-based battery technology. Al-ion batteries therefore have the ability to take the place of Li-ion batteries in the future. Figure 12 presents an organic-aluminum battery. Reactions (3)–(5), demonstrate how electrical energy is stored and harnessed from an Al-battery system.

The anode oxidation half-reaction is

$$Al_{(s)} + 3OH^- \longrightarrow Al(OH)_{3(aq)} + 3e^- \quad E^0 = -2.31V. \tag{3}$$

The cathode reduction half-reaction is

$$O_{2(g)} + 2H_2O_{(l)} + 4e^- \longrightarrow 4OH^-_{(aq)} \quad E^0 = +0.40V. \tag{4}$$

The balanced chemical equation for the reaction becomes

$$4Al_{(s)} + 3O_{2(g)} + 6H_2O \longrightarrow 4Al(OH)_{3(aq)} \quad E^0 = +2.7V. \tag{5}$$

6. Flywheel Energy Storage Systems

The flywheel energy storage systems (FESS) are one type of energy storage technology that is now has attracted a lot of interest since it has numerous advantages over other energy storage technologies [168]. When arranged in banks, flywheels may store an unlimited amount of energy in the levels mega-joule (MJ) levels because of their high cycle life, extended working life, high round-trip efficiency, substantial power density, and low environmental impact characteristics [168].

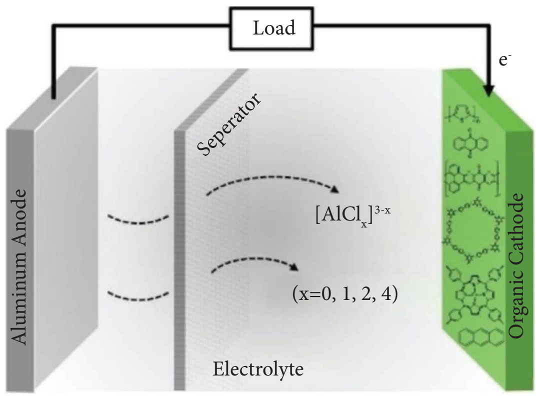

Figure 12: An assembly of organic-aluminum battery [167].

The flywheel, which serves as the main structural element of the majority of contemporary high-speed flywheel energy storage systems (FESS) (cf. Figure 13), is a sizable rotating disk supported on a stator by magnetically levitated bearings [169]. A flywheel can be used to keep machinery working smoothly and mechanically store kinetic energy from the rotor mass's fast rotation. FESS has kinetic energy that is connected to both inertia and speed. FESS can be divided into two primary categories. Low-speed flywheels are those that spin at fewer than 10,000 revolutions per minute and are more common in industries [170, 171]. The low-speed FESS has a steel disk with a high moment of inertia [172]. Fast-speed FESS, on the other hand, features a composite disk with a relatively low moment of inertia and fast speed. The stored energy grows proportionally to the rotor's rotational speed and fluctuates in a square relationship to its angular momentum. By slowing down the rotor torque (discharge mode) as well as transferring the kinetic energy back to the electrical motor, which serves as a generator, more may be done with the stored energy. Moreover, parallel flywheel additions can be made to boost the specific energy. From low (5 Wh/kg) speed to high (100 Wh/kg) speed, the energy concentration varies [24, 173]. A storage system similar to FESS can function better than a battery energy storage system (BESS) in the event of a sudden shortage in the production of power from renewable sources, such as solar or wind sources [174]. In the revolving mass of the FESS, electrical energy is stored. Consequently, the following relations (equations (6) and (7)) can be used to determine how much energy is stored in the flywheel.

$$E_{fw} = \frac{1}{2} J \times \omega^2, \tag{6}$$

$$\frac{1}{2} m \times r^2 = \frac{1}{2} p \times h \times \pi \times r^4. \tag{7}$$

here, ω, m, r, h, and E_{fw} are the flywheel's angular velocity, mass, radius, length, and mass density, respectively, whereas J is the flywheel's moment of inertia.

Flywheels, which compete with other storage technologies in applications for electrical energy storage, as well as in transportation, military applications, and satellites in space, have the main characteristics of high energy efficiency, high power, and energy density. They carry out numerous significant energy storage applications in a power system with storage capacities of up to 500 MJ and power ranges of kW to GW [168].

6.1. The Flywheel as an Energy Storage System. One of the earliest mechanical energy storage devices is the flywheel, which has been used for storing energy for centuries. For instance, the flywheel effect was employed to keep the potter's wheel rotating while still maintaining its energy. Similar rotating devices, such as the water wheel, lathe, hand mills, and other rotary devices used by humans and other animals, performed flywheel applications [175]. These medieval spinning wheels are identical to those used in the 19th and the 20th centuries. Flywheels were then utilized in factories as energy accumulators as well as on steam-powered boats and railways. Due to advancement in cast iron and cast steel in the middle of the 19th century, extremely huge flywheels with curved spokes were constructed [176].

Basically, a flywheel is a device that uses the rotating mass theory to store energy [177]. It is a mechanical energy storage system that transforms electrical energy into mechanical energy to simulate the storage of electrical energy [178]. The kinetic energy of rotation is the principal of how a flywheel stores its energy. Typically, an electrical source from the grid or any other source of electrical energy is used as the input energy for FESS [168]. To deliver the stored energy, the flywheel accelerates as it stores energy and decelerates as it discharges that energy. An electrical motor generator (MG) that converts electrical energy into mechanical energy and mechanical energy into electrical energy powers the rotating flywheel [179].

When energy is needed, the flywheel's rotational energy is converted back into energy by a generator [180]. Therefore, the flywheel is accelerated to store energy when it is available [5]. Grid stabilization and uninterruptible power supplies are two important aspects of the flywheel. Flywheels can react quickly to changes in demand and have quick reaction times. They can function at high efficiency, and in comparison to other energy storage devices, they have a comparatively long lifespan. However, due to energy loss occasioned by friction and other variables over time, FES is often not as suited for long-duration energy storage as other technologies, including pumped hydroelectric storage or battery storage [5].

7. Bio-Inspired Batteries

7.1. Moringa Paste-Based Battery. A future alternative to clean and ecofriendly energy is the effective use of sustainable green energy without destroying natural resources or hurting the environment [181]. This has assumed a critical phase in the development of sustainable intermittently efficient energy storage bio-systems [182]. Moringa (*Moringa oleifera*) paste may be used as a bio-battery to provide environmentally friendly electricity. The primary electrolyte

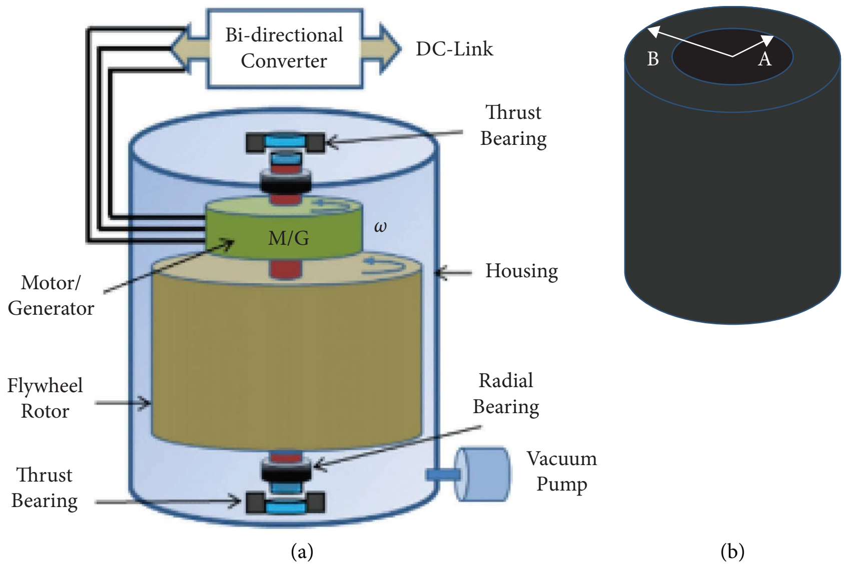

Figure 13: The principal structure of flywheel energy storage system (a) and (b) hollow cylinder flywheel [168].

component for high-capacity green production electrical energy storage devices is anticipated to be the organic compounds from the Moringa plant [183]. Electrochemical performance will result from the Moringa extract dissolving in water like typical organic electrolytes. It is remarkable to note that the organic Moringa electrolyte solution has a high ionic conductivity, can solve the solubility in liquids, and has an acidic pH. This is extremely robust because a good battery should not include any heavy metals.

Researchers from Japan are credited for popularizing the term "bio-battery," which refers to a device for storing energy that is powered by bio-organic/bio-molecular chemicals [183, 184]. They indicated that the sources of bio-batteries are amino acids, enzymes, glucose, and carbohydrates resulting in a solid-state battery with organic flow and high energy density. Bio-batteries exhibit strong organic, steric, and electronic qualities for high capacity and voltaic efficiency, which can be accessed by tracking the charge state as a function of time. As a result, it has a moderately high duty cycle, makes good use of its material, and has a better voltaic performance that is comparatively high. According to Therik , the Moringa electrolyte paste materials have shown modest performance as can be observed in Table 2 [183].

7.2. Vegetable Electroactive Antioxidants for Rechargeable Bio-Batteries. Because of their promising potential as a special platform for sustainable energy, biofuel cells have been in the focus for the past century. Bio-batteries have been used interchangeably with biofuel cells since they are often designed on compact platforms that can function as a primary battery with little fuel or as a rechargeable battery with frequent recharging [185, 186]. The sustainability of biofuel cell development is affected by their poor performance, instability, operational challenges, and irregular and erratic power generation. The development in bio-electro-catalysis, however, has revolutionized the ability of biofuel cells to generate power and boasts the promise of an appealing and useful approach for specific applications [187].

Due to an imbalance in supply, pricing, and demand, vegetables frequently decay or are out of stock in the market. Vegetable waste and untamed plants have electrochemically active chemicals that can be used to produce rechargeable bio-battery cells [188]. In order to increase the output voltage, the reaction conditions should be improved and the fresh and cooked juices of these vegetable and wild plant combinations should be utilized [188]. For various charging timeframes, juice volume, charging voltage, pH of cell media, and the output voltage are determined before and after charging of the cells [188, 189]. By switching the type of the media from acidic to neutral and neutral to basic, the impact of the media can be explored. In contrast to bio-batteries, a biofuel cell is made up of the anode and cathode electrodes, which are separated by a liquid electrolyte, and a membrane that controls the flow of ions between the two electrodes. Through an external circuit, the electrons are generated at the anode and join with the proton at the cathode. Bio-batteries can be divided into three categories: those that use microbes to produce electricity, those that use enzymes for redox processes, and those that combine easily oxidizable and reducible biomolecules with other organic substances [190]. The term "bio-battery" in this context solely refers to rechargeable batteries that produce and store electricity using biomass materials. Figure 14 shows two prototype bio-batteries based on enzymes and microbes.

The traditional method of producing power using fossil fuels has given way to systems that incorporates cutting-edge renewable energy technologies [191, 192]. Battery-based energy storage is one of the most significant and effective methods for storing electrical energy. The optimum mix of efficiency, cost, and flexibility is provided by the electrochemical energy storage device, which has become

Table 2: Electric voltage and current measurements in Moringa paste extract [183].

Moringa leaf solid extract	Voltage (V)	Current (mA)	Watt (mW)	Extract volume (gram)
Leaf extract	0.49	0.60	29.4	20

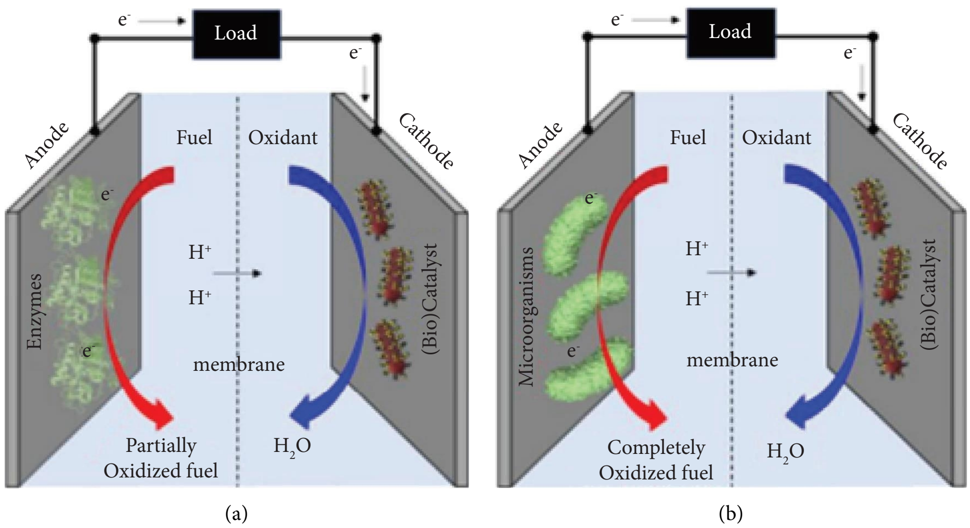

Figure 14: Enzymatic fuel cells (a) and (b) microbial fuel cells [185].

indispensable to modern living. A positively charged cathode electrode, a negatively charged anode electrode, along an electrolyte system that promotes the steady flow of electrons, make up a battery, which stores power produced by redox chemical reactions [193, 194]. Most commonly used batteries are made primarily of inorganic metals such as copper, zinc, lithium, tin, nickel, and cadmium [195, 196]. However, the majorities of these metals are not only expensive but also poisonous, and nonbiodegradable, and thus have an adverse effect on the environment. Therefore, a number of studies have been focused on designing renewable energy sources that are environmentally friendly and cost-effective. As potential substitutes for cathodes, anodes, and electrolytes in batteries, a number of biomaterials have been investigated. A biomaterial must be biodegradable and have favorable physico-chemical characteristics that would permit large charge storage densities with no negative economic impact in order to function as an efficient anode in energy storage devices. In comparison to chemical-based energy systems, a bio-battery has intrinsic advantages such as high efficiency at room temperature and near neutral pH, low cost of production, and simplicity in miniaturization and is environmentally benign.

7.3. Quinones as High Power Density Biofuel Cells. Plants naturally produce quinones, which serve as the primary structural components for electron transmission as well as energy storage during photosynthesis [197]. In order to build energy conversion and harvesting systems that are inspired by biological processes, these special qualities of quinone and its byproducts are currently being explored. The question of whether ordinary plant extracts could be utilized as redox molecules in bio-batteries has been investigated before [198]. *Lawsonia inermis* (henna) was used to extract natural quinone molecules that were then purified using column chromatography [199, 200]. The natural quinone molecules were then tested for possible use as redox molecules in a bio-battery by sequentially extracting them with hexane, ethyl acetate, methanol, and 80% methanol in water. Quinones were confirmed to be present in the extracted fractions using a combination of gas chromatography-mass spectrometry (GC-MS) analysis and UV-visible spectroscopy [199]. Maximum absorbance was detected by UV analysis at 295 nm and 450 nm, respectively, which are associated with 4-t-butyl-1,2-benzoquinone and duroquinone [199]. In addition, tocopherol (vitamin E), which is a possible redox molecule, was confirmed by GC-MS analysis as of the henna extract.

8. Batteries for Nonaqueous Flow That Use Organic Solvents

Nonaqueous redox flow batteries (RFBs) as presented in Figure 15 are made with organic solvents and can be classified as organic, metal-ligand, or semisolid [202]. The valence electrons in organic molecules pair as distinct molecular orbitals (MOS), which are typical uncharged compounds without significant net electron spin [203]. However, by bond homolysis, free radicals can easily produce species with single-occupied molecular orbitals (SOMO). Radical coupling or dimerization is relatively simple because the majority of free radicals are active due to their energetically favorable spin. Additionally, a free radical chain reaction may result from the free radical reaction with

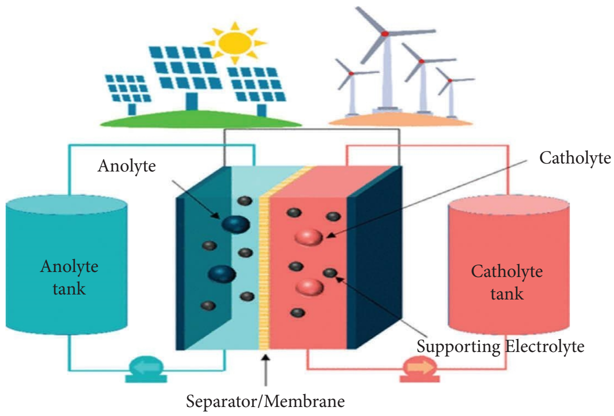

Figure 15: An assembly of a redox flow battery [201].

spin molecules via the abstraction or addition process, which can also cause free radicals to diffuse to other molecules [204]. In order to create redox-active solutions known as anolytes and catholytes, both anode and cathode materials are dissolved in solvents that include supporting electrolytes [201].

8.1. Ionic Liquid Solvent-Based Non-Aqueous Flow Batteries. Ionic liquids are well suited for use as electrolytes due to their strong ionic conductivity, low volatility, high electrochemical stability, tunable solubility, polarity, and charge distribution, among other robust properties [205]. The van der Waals and Coulombic forces, as well as the presence of Lewis acidity or basicity in their structures, interact with cations and anions to define these properties [206]. High conductivity, viscosity in addition to surface tension of deep eutectic solvents (DESs) makes them desirable for electrochemical applications. DESs have the potential for wide-scale application and can be produced by utilizing affordable and biodegradable precursors such as oxalic acid and urea [207].

8.2. Self-Discharge Redox Flow Batteries. One type of electrochemical energy storage technology is represented by redox flow batteries (RFB). The term "redox" refers to chemical reduction and oxidation reactions used in the RFB to store energy in liquid electrolyte solutions that flow through an electrochemical cell battery during charge and discharge cycles. Due to their decoupling of capacity as well as power, quick response, long lifespan, and structural simplicity, RFBs have gained considerable attention in the field of large-scale energy storage [203]. RFBs with aqueous electrolytes have difficulty achieving large energy densities due to the restricted open circuit voltage (Voc) produced by oxygen and hydrogen evolution processes and the relatively poor solubility of active species [208]. Two half cells with dissolved redox systems and various redox potentials that combine to form the cell voltage are connected by an appropriate separator in a redox flow battery (RFB). Non-aqueous solvents, however, are also constrained by certain significant problems, such as excessive viscosity as well as poor safety. The nonaqueous flow battery (NAFB) system's multivariable functioning and relevant structural design parameters must be thoroughly understood in order to mitigate these drawbacks [203]. Modeling and simulation are not only useful for understanding the fundamental operations of flow batteries at various time and size scales, but they are also an excellent tool for enhancing the reaction process, battery assembly, and overall flow battery installation [209].

To prevent chemical interactions between the active substances in the two solutions, which could cause the cell to discharge, both solutions must be kept apart. In the majority of device designs, this separation is created by inserting an ion-conducting membrane that is semipermeable [210]. Additional solutions are being considered, such as porous separators for systems with larger redox ions. Ion crossover, or the unintentional mixing of redox components, can lead to direct chemical reactions and unintentional cell heating, which in turn can lead to self-discharge in RFBs [210]. Chemical interactions between redox constituents and cell components, such as the oxidation of electrode materials in the positive electrode half-cell by highly oxidizing substances are additional mechanisms that lead to self-discharge. Energy is also used by additional auxiliary devices required to monitor and regulate the RFB's proper operations [211]. This will also require the expenditure of electrical energy, most likely taken from the energy initially stored in the device, just like devices that monitor the state of a battery module or a battery pack. Self-discharge brought on by ion crossing is strongly tied to flaws in the separator being employed, whether it be a very porous material or a semi-permeable membrane. Redox-active electrolyte elements that are large enough in the solvated form to slow down or even prevent passage across the membrane are another way to limit ion crossover [210]. Two electrolyte tanks (anodic and cathodic reservoirs), anodic- and cathodic-active substances (anolyte and catholyte), an ion-exchange membrane, and the battery architecture make up the majority of RFBs (cf. Figure 16).

Using a half-cell made of cerium has also led to the observation of self-discharge through ion crossing. Self-discharge may also happen from the oxidation of cations in the negative half-cell, for example, an all-vanadium RFB, by dioxygen from ambient air in a mostly open system [210]. The indicated treatments are clear-cut: higher electrolyte concentrations appear to also slow down the oxidation of V(II) by dioxygen despite the clear reduction in the surface area of the electrolyte solution reservoir exposed to the atmosphere [210].

8.3. A Hybrid Zn-Fe Redox Flow Battery without Dendrites. The burning of fossil fuels for energy accounts for over two thirds of the world's greenhouse gas emissions, which has sparked intense research interest in the production of renewable energy technologies based on wind, solar, and other energy sources [21]. Widespread interest is being given to redox flow batteries (RFB) as scalable energy storage solutions to deal with the intermittent nature of renewable

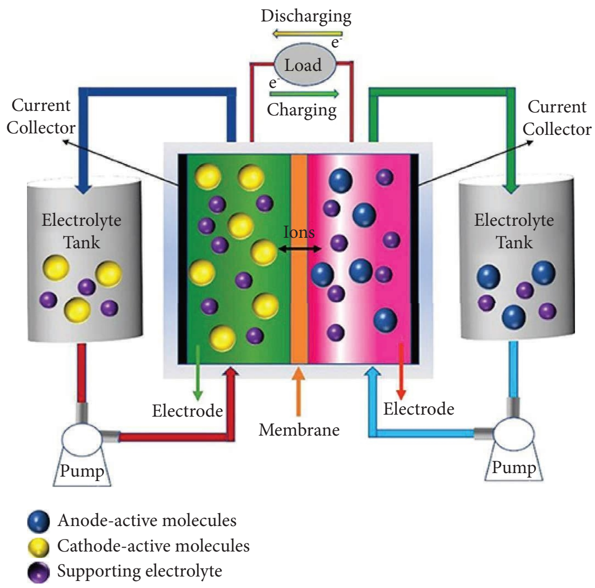

Figure 16: An assembly of a standard redox flow battery [212].

energy sources [213]. The redox flow batteries must be both economically and environmentally sound to be widely commercialized. Because zinc is widely available on Earth and has a moderate specific capacity of 820 mA·hg and a high volumetric capacity of 5851 mAh·cm^3, zinc-based batteries are good energy storage devices [213]. Redox flow batteries (RFBs) are remarkable electrochemical devices that, in contrast to conventional batteries, store energy in two electrolyte solutions [214] made up of various redox couples that are divided by an ion-exchange membrane (IEM) [215]. The hybrid flow batteries are one type of conventional flow batteries that involves covering at least one electrode with metal [216].

The key benefits of RFBs in comparison to other battery systems are their flexibility in charge-discharge cycles, reasonable cost, adaptability, and safety. Unfortunately, this results in unintended redox species crossover between both positive and negative electrolytes through the membrane because of the insufficient ionic selectivity of the present IEMs [217]. As a result, the Coulombic efficiency (CE) as well as battery capacity are permanently lost, which affects RFBs' overall performance. A self-made anion exchange membrane separates the two redox couples in a zinc-iron hybrid redox flow battery (Zn/Fe hybrid RFB), which uses Zn/Zn (II) and Fe(II)/Fe(III) redox couples as negative and positive redox materials, respectively [218]. Because of their low cost as well as abundance, zinc and iron are the two best elements for energy storage. Due to its quick kinetics, the ferric/ferrous chloride redox pair that has been utilized in a number of flow battery systems shows promise as an active component. Sheets of densified graphite have been used as the electrodes, while acrylic sheets have been used as the cell housings [213]. The Fe^{2+} ions at the negative electrode pick up these electrons during battery charging and electro-deposit them as metallic Fe; the Fe^{2+} ions at the positive electrode release the electrons and oxidize to become Fe^{3+} ions [218]. Chloride ions pass across the anion exchange membrane from the negative electrolyte into the positive electrolyte to maintain charge neutrality. In the course of battery discharge, these processes are inverted. Figure 17 demonstrates the operational characteristics of an all-Fe RFB energy storage device. The all-Fe RFB operates on the principles described by reaction (8)–(10), herein presented, which demonstrate how electricity is stored and released from the device while charging [218].

$$Fe^{2+}_{(aq)} + 2e \rightleftharpoons Fe_{(l)} \quad E^0 = 0.44V, \tag{8}$$

$$2Fe^{2+}_{(aq)} \rightleftharpoons 2Fe^{3+}_{(aq)} + 2e \quad E^0 = 0.77V, \tag{9}$$

$$3Fe^{2+}_{(aq)} \rightleftharpoons 2Fe^{3+}_{(aq)} \quad E^0 = 1.21V. \tag{10}$$

Figure 17 gives the Zn-Fe hybrid redox flow battery schematically. The following electrochemical reactions (Reactions (11)–(13)) can be used to illustrate how Zn-Fe RFB stores and releases energy in the form of electricity.

$$\text{Anode rxn: } Zn^{2+}_{(aq)} + 2e \rightleftharpoons Zn_{(s)} \quad E^0 = -0.76V \tag{11}$$

$$\text{Cathode rxn: } 2Fe^{2+}_{(aq)} \rightleftharpoons 2Fe^{3+}_{(aq)} + 2e \quad E^0 = +0.77V \tag{12}$$

$$\text{Overall rxn: } Zn^{2+}_{(aq)} + 2Fe^{2+}_{(aq)} \rightleftharpoons Zn_{(s)} + 2Fe^{3+}_{(aq)} \quad E^0 = +1.53V \tag{13}$$

9. Self-Discharge of Battery Storage Systems

Batteries can self-discharge, which is a common but unwanted phenomenon in energy storage technologies [219, 220]. It can only be slowed down by inhibiting the reaction kinetics of its many steps, or their respective rates of reaction, because it is driven in all of its forms by the same thermodynamic forces as the discharge during normal device operation. In an ideal world, a secondary battery that has been fully charged up to its rated capacity would be able to maintain energy in chemical compounds for an infinite amount of time (i.e., infinite charge retention time); a primary battery would be able to maintain electric energy produced during its production in chemical compounds without any loss for an infinite amount of time. Since a main battery cannot be replenished, the problem of self-discharge with the latter appears to be more urgent. Unfortunately, reality is different, but a secondary battery may be recharged provided a source of electric energy is available [221]. In thermodynamic terms, a brand-new main battery and a charged secondary battery are in an energetically greater condition, implying that the corresponding absolute value of free enthalpy (Gibb's free energy) is higher [222, 223]. Distinguishing statements must take into account the fact that discharge is a spontaneous process, which results in values carrying a negative sign. The device aims to reach an equilibrium condition in which the driving force for discharge as well as release of electric energy is spent and the free enthalpy in the discharged state must be equal to zero. The latter is extremely undesirable,

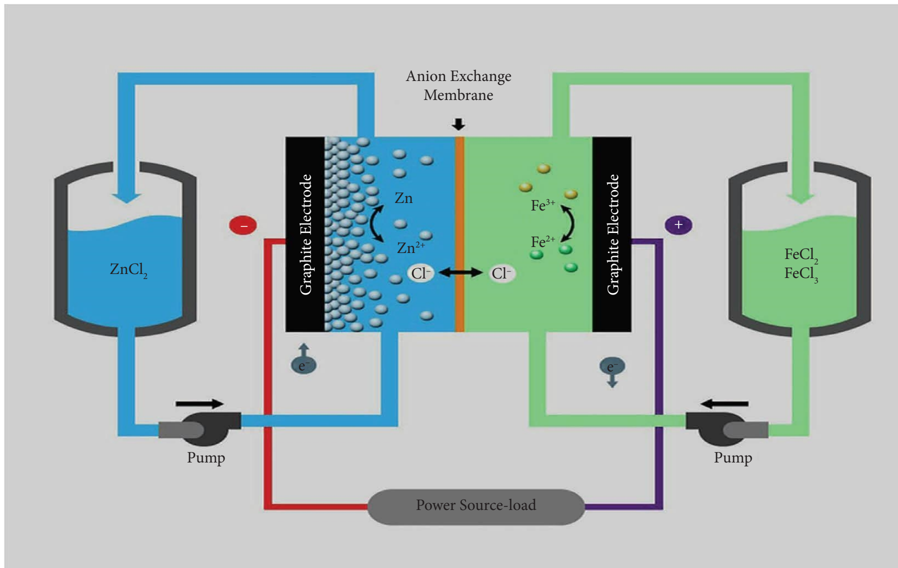

Figure 17: An assembly of an all-Fe RFB [213].

but due to thermodynamic limitations, self-discharge can only be prevented by slowing down the kinetics of the processes that lead to it [210]. This chiefly relates to chemical processes that generate self-discharge, though parasitic currents with origins other than thermodynamics can also enhance self-discharge. The operational chemical, electrical effects as well as descriptions can be summed up into the need to decrease these unwanted current(s) since self-discharge can be conceptualized from an electrical engineering point of view as the passage of an unwanted current. This current, which is also known as the leak current, can be represented as a shunt resistor in an equivalent circuit representation of a cell [224]. Beyond the kind of electrolyte solution, the chemical reactions that cause self-discharge heavily depend on battery chemistry and electrode materials. Self-discharge-related reactions are all chemical or electrochemical processes [210, 225].

Self-discharge is a characteristic found in numerous electrochemical storage devices along with conversion systems that cannot be completely eliminated because they are thermodynamically unstable by nature or contain molecules that are unstable relative to others [226, 227]. Self-discharge has frequently been decreased through better cell design as well as careful selection of materials with clearly specified features and composition [210]. A brief comparison between primary and secondary cells is presented in Table 3.

Secondary cells' tendency to release themselves more quickly after lengthy cycling and in older cells may be a result, at least in part, of the degradation of additional inhibitors such as those found, for example, in the electrolyte solution of alkaline batteries or the creation of electrode reaction products that function as catalysts for unintended reactions that cause self-discharge. The only time self-discharge is impossible is when the reactive compounds are totally separated; this can be done using reserve batteries or, for instance, by draining the electrolyte solutions from a redox flow battery [210].

9.1. Parasitic Current-Induced Self-Discharge. Batteries can self-discharge, which is a natural but very unpleasant phenomenon. It can only be slowed down by inhibiting the reaction kinetics of its individual steps, or their respective rates of reaction, because it is driven in various forms by the same thermodynamic forces as the discharge during intended device operation. This strategy is founded on a deeper understanding of the numerous self-discharge modes and mechanisms, which depend on the chemistry of the battery, how it operates, and the external environment [210]. In thermodynamic terms, a new main battery as well as a charged secondary battery is in an energetically higher condition than in the discharged or depleted state, which means the corresponding absolute value of Gibbs energy is higher [228]. Discharge is a spontaneous process, hence because the values have a negative sign, characterizing statements and equations must reflect this. Thermodynamic equilibrium is far from being reached in this charged state [229]. The device aims to reach an equilibrium state when the free enthalpy equals zero and there is no more electric energy to drive discharge. Furthermore, to the desired method of entering this condition by controlled discharge, there are additional, unfortunate, and self-discharge-related approaches that are feasible [230]. The latter is extremely undesirable, but due to thermodynamic constraints, self-discharge can only be reduced by as much as possible by slowing down the kinetics of the processes. This primarily relates to chemical reactions that induce self-discharge, though parasitic currents with nonthermodynamic sources.

The detection and mitigation of catastrophic battery failure caused by an internal short are incredibly challenging. Battery self-discharge results from internal battery reactions that drain stored energy when there is no external circuit connection. In other words, even when the linked program is not consuming any energy, the battery, nevertheless, loses energy. The outside temperature, the battery's level of charge, the battery's design, the charging current, as well as

Table 3: Normal self-discharge rates when the temperature is ambient [210].

Class	System	Self-discharge
Primary	Alkali-manganese cell	0.5% per month
	Leclanche cell	0.5% per month
	Lithium/	0.5% per month
	Lithium-ion	<10% per decade
Secondary	LSD-NiMH	4% per month
	NiCd	20% per month
	RAM	0.5% per moth
For comparison: Supercapacitor	EDLC	1.8% per day

LSD: low self-discharge; RAM: rechargeable alkali manganese; EDLC: electrochemical double layer capacitor.

other variables, can all affect how quickly a battery discharges itself [231, 232]. Comparing primary batteries to rechargeable chemistries, self-discharge rates are often lower in primary batteries. The passage of an electric current even when the battery-operated device is turned off may be the result of leakage caused [233], for example, by electronically slightly conductive residues of dirt on the battery surface, the battery holder, or mechanical and chemical processes inside the battery [234]. This current flow may also occur within the cell as a result of parasitic electric connections between active masses or incompletely insulating separators. Nevertheless, careful planning and management of the cell and its surroundings can prevent battery self-discharge.

9.2. Self-Discharge in Aqueous Batteries. Self-discharge in aqueous-based batteries is largely brought about by the reactivity of the electrode materials with water and the passage of ions through the electrolyte. Modern electrolyte modification methods have enabled the development of metal-air batteries, which has opened up a wide range of design options for the next-generation power sources. In a secondary battery, energy is stored by using electric power to drive a chemical reaction. The resultant materials are “richer in energy” than the constituents of the discharged device [210]. Currently, there are three components that make up the self-discharge mechanism in supercapacitors: (1) ohmic leakage, (2) parasitic Faradaic reaction, and (3) charge redistribution (Figures 18(a)–18(c)).

In sealed cells with a little quantity of phosphoric acid added to the sulphuric acid electrolyte solution, self-discharge is reduced; the cells are of the “starved type,” meaning there is no free solution [210]. The presence of phosphoric acid is responsible for the slower self-discharge; the expander in the negative electrode has no impact on self-discharge [210]. The process described above during routine discharge is known as the cell response. Both parasitic electrode reactions continue for as long as their respective electrode potentials are active. While the unwanted process may continue, the impurity ions themselves are not destroyed. The electrode potential may not be as advantageous for the parasitic reactions as the discharge progresses because the electrode potentials move closer to one another [236, 237]. In the course of operation, additives to electrodes and/or electrolyte solutions, such as the expanders in lead-acid batteries, may breakdown, thus producing either catalysts for reactions like hydrogen evolution that contribute to self-discharge or mechanisms for shuttling [238]. In a lead-acid battery, antimony alloyed into the grid for the positive electrode may corrode and end up in the electrolyte solution that is ultimately deposited onto the negative electrode. Here, it catalyzes the evolution of hydrogen, which lowers charging efficiency and raises self-discharge activity [239]. Calcium has been suggested as an alternative to antimony, which results in less gas evolution and self-discharge rates [240].

9.3. Strategies for Reducing Self-Discharge in Energy Storage Batteries. Low temperature storage of batteries slows the pace of self-discharge and protects the battery’s initial energy. As a passivation layer forms on the electrodes over time, self-discharge is also believed to be reduced significantly. Researchers have attempted to increase the size of the electrode/electrolyte contact since electrode reactions are by nature heterogeneous processes [241]. Any increase in the surface area will aid both the desired and undesirable electrode reactions because the majority of self-discharge reactions are also heterogeneous processes. In order to avoid enhancing self-discharge and possibly consuming active material during the formation of surface layers, it is important to maintain optimized electrode morphology in terms of surface area and porosity [242]. This should not change significantly during charge/discharge (for example, by the disintegration of active mass particles caused by volume expansion or pulverization initiated otherwise). This has been applied to both aqueous and nonaqueous electrolyte solutions to add chemicals to the electrolyte solution. Their roles range from preventing parasitic electrode reactions to binding unwanted and harmful contaminants that are introduced by the electrodes and/or electrolyte solution to catalyzing procedures that remove undesirable species [243]. Avoiding overcharging batteries of all kinds seems to be a quick and easy way to keep them healthy and lessen subsequent self-discharge and improve the lifetime of the battery [244].

Figure 19 demonstrates that batteries can store 2 to 10 times their initial primary energy over the course of their lifetime. According to estimates, the comparable numbers for CAES and PHS are 240 and 210, respectively. These numbers are based on 25,000 cycles of conservative cycle life estimations for PHS and CAES.

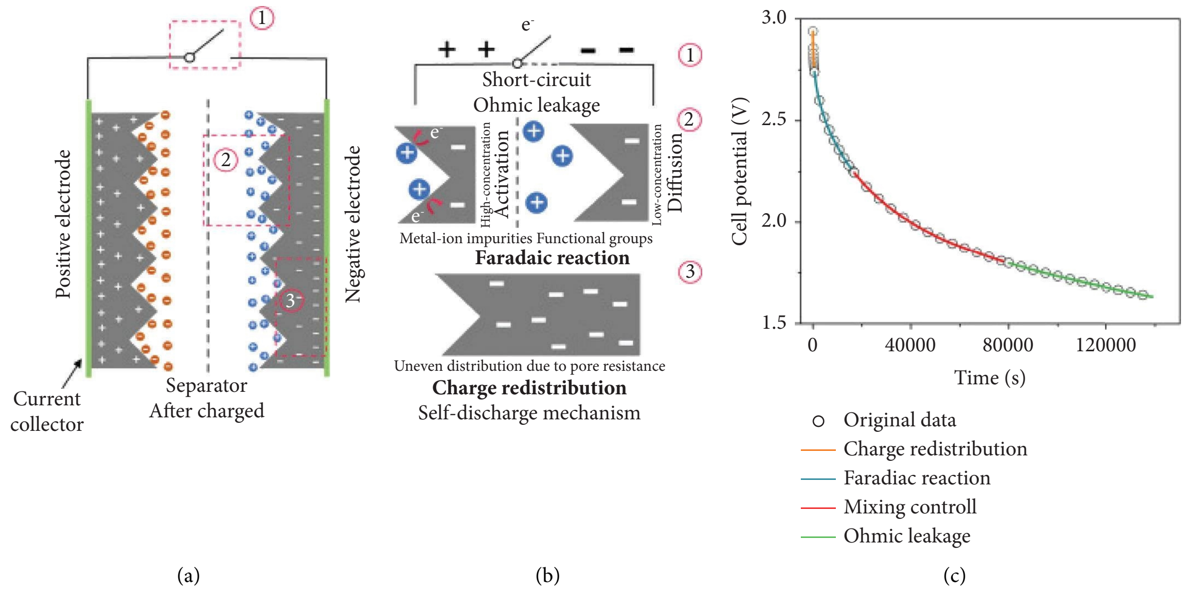

Figure 18: Supercapacitor self-discharge mechanism. (a) Charging, (b) the separate self-discharge mechanisms, and (c) self-discharge decay curve [235].

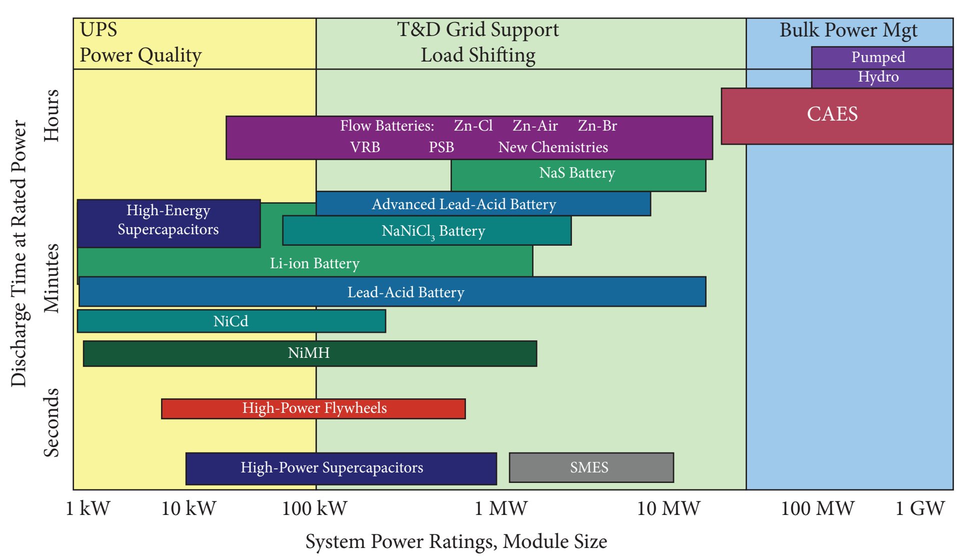

Figure 19: Energy storage devices' ability to meet various power and discharge rate criteria [245].

Because of the need to reduce greenhouse gas emissions and use blended energy sources, electrical power generation is changing drastically all in the world. In order to meet demand with unpredictable daily and seasonal variations, the electricity network faces enormous hurdles in transmission and distribution. Electrical energy storage (EES), in which energy is stored in a specific state, depending on the technology utilized, and is converted to electrical energy when needed, is acknowledged as an underlying technology with significant potential for addressing these challenges. However, it is difficult to evaluate a single EES technology for a certain application due to the vast array of alternatives and complicated characteristic matrices.

Energy storage technologies exhibit diverse power ratings and discharge durations. Lithium-ion batteries, with power ranging from a few watts to megawatts, offer discharge times spanning from minutes to several hours [246]. They find extensive use in portable devices, electric vehicles, and grid storage. Lead-acid batteries, typically employed in low-to-medium power scenarios (from a few watts to hundreds of kilowatts), cater for short to medium discharges, lasting minutes to a few hours [170]. They serve automotive starting batteries, backup power systems, and off-grid solar energy storage. Flow batteries, such as vanadium redox and zinc-bromine variants, provide power from kilowatts to megawatts and offer extended discharge windows, spanning hours to days [247].

Their suitability lies in grid-scale energy storage due to their capacity for large energy storage and prolonged discharges. Supercapacitors, with lower power ratings than batteries but higher power density (ranging from a few watts to hundreds of kilowatts), boast very short discharge times, lasting seconds to minutes [248]. They find application in scenarios requiring high power bursts like vehicle regenerative braking or brief power backup needs [249]. Pumped hydro storage operates on a gigawatt scale, delivering power for hours to days [250]. This method involves pumping water to an elevated reservoir and releasing it to generate electricity, predominantly used for large-scale grid energy storage. Flywheel energy storage, spanning from kilowatts to megawatts, supplies power for seconds to minutes, suitable for situations necessitating high power for short durations, such as stabilizing electrical grids [251]. Thermal energy storage (TES), with variable power ratings, can store energy for hours to days [252]. It is employed in storing surplus thermal energy from renewable sources such as solar or geothermal, releasing it as needed for heating or power generation. Figure 20 presents energy storage technology types, their storage capacities, and their discharge times when applied to power systems.

The selection of an energy storage technology hinges on multiple factors, including power needs, discharge duration, cost, efficiency, and specific application requirements [246]. Each technology presents its own strengths and limitations, rendering them suitable for distinct roles in the energy landscape. Every technology possesses distinct discharge characteristics, capacity, efficiency, and application compatibility [254]. Whether the option is for grid-scale storage, portable devices, electric vehicles, renewable energy integration, or other considerations, the decision is frequently based on factors such as required energy capacity, discharge time, cost, efficiency, as well as the intended application.

9.4. Risks Associated with Energy Storage Batteries. Storage batteries are available in a range of chemistries and designs, which have a direct bearing on how fires grow and spread. The applicability of potential response strategies and technology may be constrained by this wide range. Off gassing: toxic and extremely combustible vapors are emitted from battery energy storage systems [255]. Depending on the battery chemistry involved, the type of gas discharged may vary, although it frequently contains gases like carbon monoxide, carbon dioxide, hydrogen, methane, ethane, and various other hydrocarbons. Lithium-ion battery technology has been extensively tested in fire environments. The influence of lithium-ion battery fire development will need to be predicted inductively since there have only been a few numbers of lithium-ion battery fire tests conducted in subterranean and tunnel environments [221].

Under favorable circumstances, an explosion could occur as a result of the expelled fumes from a failed LIB, which includes combustible material. The flammable gases can also build up within an enclosure since the vented gases are made up of a variety of densities [256]. Although there is a little chance that an explosion from a failing LIB cell may occur, the intensity of the explosion if it does warrants consideration of this risk. Lower flammability limit (LFL) of vented gases, flame speed, and maximum adiabatic overpressure are three gas characteristics that determine the severity of an explosion [257].

The concept of thermal stability is crucial in relation to fire safety in energy storage batteries. Thermal stability is a measure of safety independent of the temperature at which exothermic processes would be activated, according to [258]. It is defined as the quantity of heat generated per unit time once exothermic reactions have been triggered. According to this concept, the safer a material is, the higher its level of thermal stability. Thermal stability, along with LIB chemistry, state of charge (SOC), capacity, and cell packing, is only one factor that affects the heat of combustion. The rate at which heat is released (HRR), peak heat release rate (PHRR), growth rate, as well as radiative heat flux, are important factors to measure the intensity of a fire occurrence [259]. Because of their high energy density, favorable environmental impact, and low price, energy storage technologies such as batteries have significant societal significance. However, there are still important problems that must be fixed in order to ensure their performance and safety.

Certain factors for the detection of fires should be taken into account due to the breakdown progression for storage batteries. Use of detection equipment that is specifically designed for the installation's energy storage chemistry and capacity, choose the best site to mount the chosen detection technology, and increase early detection of battery safety problems prior to, during, and following a fire incident. A typical occurrence observed in rechargeable batteries is the degraded capacity, also known as capacity loss or capacity fading [260]. In this phenomenon, the charge produced by the battery at a rated voltage decreases with time following continuous use. The operating temperature of a battery affects capacity loss; the aging rate is inversely related to temperature below 30°C and directly proportional to the temperature above 30°C. The charging rate affects capacity loss, and the greater charging rates result in a quicker rate of capacity loss.

In summary, energy storage systems advance a critical technological component in storing excess energy generated by renewable sources like solar and wind during peak production times for later use when demand is high or when these sources are not generating power [252]. They ensure a steady and reliable supply of electricity, addressing the intermittent nature of renewable energy sources. Moreover, energy storage technologies contribute significantly to clean and ecofriendly energy initiatives by enabling the integration of renewable energy sources into the conventional grid [261]. By storing energy efficiently, they help reduce reliance on fossil fuels, thereby minimizing air and water pollution associated with traditional energy generation [262]. Also, energy storage systems help in reducing carbon footprint and greenhouse gas emissions by facilitating the transition towards renewable energy [263]. In the process of storing surplus clean energy and making it available when needed, they lessen the dependency on fossil fuels, subsequently decreasing emissions responsible for climate change,

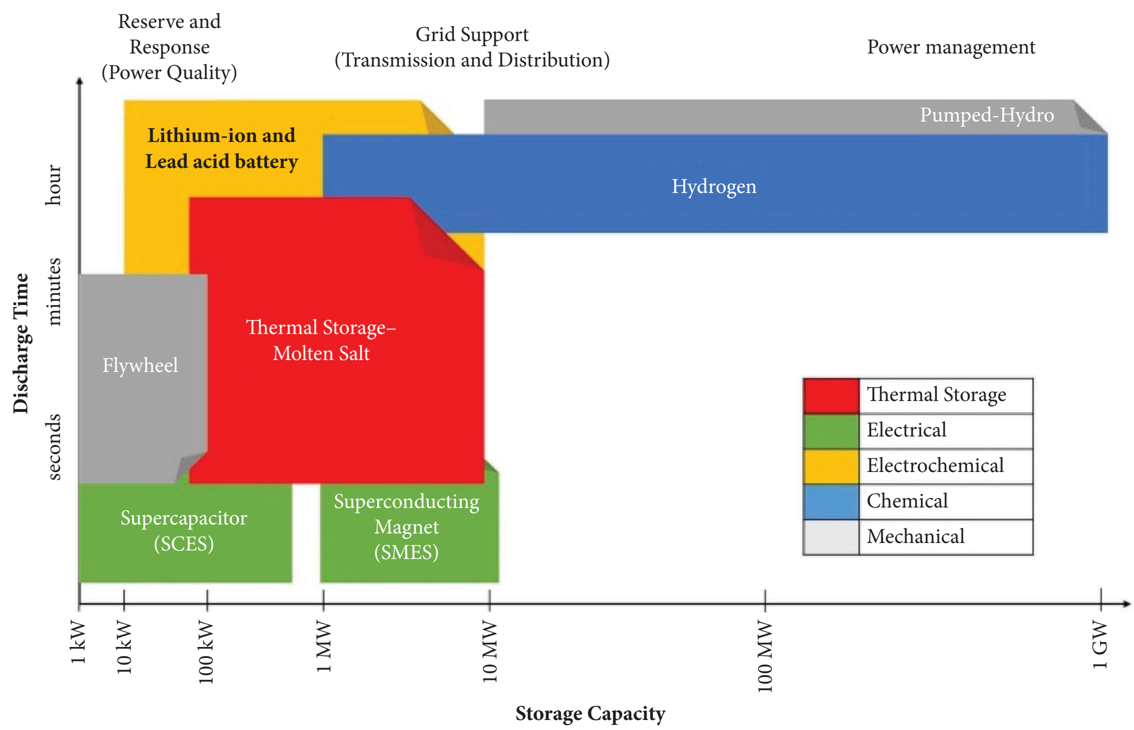

FIGURE 20: Energy storage technology in power system applications according to storage capacity and discharge time [253].

consequently accelerating climate adaptation strategies, and are catalysts towards achieving a net-zero carbon future [264]. Their ability to store renewable energy efficiently ensures a continuous and reliable power supply without relying on carbon-intensive sources, hence contributing significantly to achieving carbon neutrality goals across various sectors [265]. In off-grid systems, where traditional power sources are unavailable or impractical, energy storage becomes essential. They enable the capture and storage of excess energy, ensuring a consistent power supply even in remote or isolated areas, thus promoting sustainability and self-reliance in energy generation and utilization [266]. Overall, energy storage systems play a crucial role in reshaping the energy landscape towards energy sustainability, energy security, and lower environmental impact.

10. A Summary of the Advancements in Energy Storage Devices

Flywheel energy storage systems possess notable advantages, such as high efficiency during both charging and discharging phases and a rapid response time for grid balancing. Nonetheless, they are constrained by their limited energy storage capacity when compared to alternative options, alongside their high initial costs. Bio-inspired batteries, which utilize sustainable and abundant materials, present a promising avenue with potential for low environmental impact, but they are still in the developmental stage, exhibiting limited performance and scalability. Similarly, Moringa paste-based batteries offer advantages such as low cost and ready availability of materials, but they are also in the early developmental stages, lacking comprehensive performance data; however, they hold potential for deployment in rural areas in the future. Vegetable electroactive antioxidants for rechargeable bio-batteries represent a sustainable approach that could be scaled, yet their performance requires improvement for practical applications.

Quinones are high-power density biofuel cells and consequently offer high power density and are potential for miniaturization, although further investigation needs to be performed on their possible long-term stability and cost. On the other hand, organic solvent-based nonaqueous flow batteries boast high energy density and long cycle life but raise safety concerns due to the use of organic solvents. Conversely, ionic liquid solvent-based nonaqueous flow batteries provide a safer alternative but offer lower energy density compared to organic options. The hybrid Zn-Fe redox flow battery without dendrites addresses safety and stability issues compared to traditional Zn-Fe batteries, although with lower energy density. Aqueous rechargeable batteries based on organic-aluminum coupling show promise as alternatives to lithium-ion batteries but require further research for improved performance and scalability. Table 4, summarizes the most important aspects on the merits and demerits of the energy storage devices being advanced currently.

The photo-supercapacitor combines energy storage with solar energy harvesting although it suffers from limited energy density and low power output. Flexible redox-active asymmetric supercapacitors based on keratin-derived renewable carbon offer sustainability and flexibility, though performance data and scalability remain under investigation and have not been fully commercialized yet. The all-in-one flexible supercapacitor based on chemically cross-linked

Table 4: Summary of energy storage systems: merits and drawbacks.

Technology	Advantages	Disadvantages	Ref
Flywheel	(i) High efficiency round-trip	(i) Limited capacity	[267]
Bio-inspired batteries	(i) Sustainable materials	(i) Low energy density	[268]
Moringa paste batteries	(i) Low cost (ii) Locally available	(i) Short lifespan	[183]
Vegetable antioxidants batteries	(i) Biodegradable (ii) Low cost	(i) Low power density	[188]
Quinone biofuel cells	(i) High power density (ii) Renewable fuel	(i) Limited stability (ii) Complex design	[269]
Organic solvent flow batteries	(i) High scalability (ii) Fast charging	(i) Flammable solvents (ii) Safety concerns	[270]
Ionic liquid flow batteries	(i) Nonflammable (ii) Wider operating temperature	(i) High cost (ii) Limited research	[271]
Hybrid Zn-Fe flow cells	(i) Dendrite-free (ii) Long lifespan	(i) Lower energy density	[272]
Organic-aluminum cells	(i) Nontoxic (ii) Abundant materials	(i) Low power density (ii) Early-stage research	[273]
Photo-supercapacitor	(i) Self-charging with light	(i) Limited capacity (ii) Complex design	[274]
Keratin-based supercapacitor	(i) Flexible (ii) Sustainable Materials	(i) Low energy density (ii) Early-stage research	[121]
Hydrogel supercapacitor	(i) Flexible, self-healing	(i) Lower energy density, limited research	[275]
Nickel lanthanum telluride supercapacitor	(i) High energy density, flexible	(i) Complex fabrication (ii) Limited research	[276]
Electrolyte-based supercapacitors	(i) Tailored properties (ii) High performance	(i) Complex design (ii) Limited commercialization	[277]
Supercapacitors	(i) Fast charging/discharging (ii) Long lifespan	(i) Low energy density compared to batteries	[237]
Superconducting magnetic	(i) High efficiency (ii) Large capacity	(i) High cost (ii) Complex infrastructure	[278]
Compressed air	(i) Mature technology (ii) Large-scale storage	(i) Location dependent (ii) Environmental degradation	[279]
Lithium-ion batteries	(i) High energy density (ii) Mature technology	(i) Limited lifespan and safety concerns (ii) Resource limitations	[280]
Thin film solid-state batteries	(i) Comparatively Safe (ii) High energy density compared to Li-ion	(i) Early-stage research (ii) Limited commercialization	[281]

hydrogel electrolyte features flexibility and self-healing properties, yet energy density and power output require enhancement. Nickel-lanthanum telluride microfibers for redox additive electrolyte-based flexible solid-state hybrid supercapacitors exhibit high energy density and flexibility but face challenges due to complex fabrication processes and limited stability data.

Supercapacitors with an electrolyte-based design offer tailored properties for specific applications, yet performance varies with design and the materials used. While they excel in fast charging and discharging, their energy density is lower compared to conventional batteries. Superconducting magnetic energy storage devices offer high energy density and efficiency but are costly and necessitate cryogenic cooling. Compressed air energy storage, a mature technology, boasts large-scale storage capacity, although its implementation requires specific geological formations and may have environmental impacts. Lithium-ion batteries remain dominant in portable electronics and electric vehicles due to their high energy density and performance, despite concerns regarding resource limitations and environmental impact.

Thin film solid-state batteries hold the promise for improved safety and higher energy density but are still undergoing development, facing challenges in fabrication and scalability. Ultimately, the choice of an energy storage system depends on various factors such as energy density, power output, cycle life, cost, safety, and sustainability, tailored to specific needs and applications.

11. Conclusions

This review makes it clear that electrochemical energy storage systems (batteries) are the preferred ESTs to utilize when high energy and power densities, high power ranges, longer discharge times, quick response times, and high cycle efficiencies are required. Such ESTs can be used for a variety of purposes, including energy management and bridging power applications in the field of renewable energy as well as in the overall power system applications. Due to their decoupling of capacity as well as power, quick response, long lifetime, and structural simplicity, RFBs have gained considerable recognition in the field of large-scale energy storage although RFBs with aqueous electrolytes have challenges attaining large energy densities due to the restricted open circuit voltage (Voc) produced by oxygen and hydrogen evolution processes and the relatively poor solubility of active species. Notably, aqueous rechargeable batteries are highly safe, affordable, and environmentally friendly but restricted by low energy density. For grid-scale energy storage applications including RES utility grid integration, low daily self-discharge rate, quick response time, and little environmental impact, Li-ion batteries are seen as more competitive alternatives among electrochemical energy storage systems. For lithium-ion battery technology to advance, anode design is essential, particularly in terms of attaining high charging rate performance which is often required for electric vehicles (EV). In addition to switching from a carbon-based anode to one made of silicon, 3-D nanostructures have been found to be the rule of the thumb in drastically enhancing Li-ion charging rates. Low-cost additive manufacturing techniques such as electrospinning could be utilized. However, the price of the storage device must be brought down if Li-ion batteries are to be fully embraced in the renewable energy storage technologies. Li-ion batteries will become less expensive if cell technologies are improved, such as by lengthening their lifespan, shrinking their physical size, and large-scale production. Based on this review finding, Li-ion batteries are the most preferred as compared to other energy storage devices such as supercapacitors and bio-batteries. They are safer to dispose of than Ni-Cd batteries because they do not contain the hazardous metal cadmium. Li-ion batteries have replaced Ni-Cd batteries as the industry leader in portable electronic devices for applications in smartphones, laptops, electrics cars, and various electronic appliances. Energy systems are essential for gathering energy from diverse sources and transforming it into the forms needed for various applications, including those in the utility, industry, building, and transportation sectors. Energy resources such as fossil fuels can be used to meet consumer demand because they can be easily stored while not in use despised their well-established pollution impacts which have precipitated a serious climate change and serious carbon foot print on the planet. The ever-increasing demand for electricity can be met while balancing supply changes with the use of robust energy storage devices. Battery storage can help with frequency stability and control for short-term needs, and they can help with energy management or reserves for long-term needs. Storage can be employed in addition to primary generation since it allows for the production of energy during off-peak hours, which can then be stored as reserve power. In order to design and construct materials for energy storage that are of high energy density and long-term outstanding stability, state-of-the-art energy storage technologies must be advanced. By utilizing recyclable materials that are readily available in Earth's crust, keeping costs down, ensuring safe cell reactions, and achieving high performance in a single system are the key obstacles to implementing sustainable energy storage systems. High performance battery alternatives that use non-aqueous electrolytes, such as ionic liquids at room temperature based on aluminum, appear promising as a possible replacement of Li-batteries in the long run. Nevertheless, their actual performance is still at par with that of the most advanced high performance batteries. The introduction of Moringa-based bio-batteries is believed to be a game changer in the search for green energy because the electrolyte solution in Moringa has a high ionic conductivity, can solve the solubility in liquids problems, and has an acidic pH. Bio-batteries in general are environmentally friendly since they do not possess toxic metals and are easily biodegradable. Ultimately, energy storage devices will be the necessary technology for renewable energy and are promising catalysts towards decarbonization and reduction of greenhouse gas emissions. It is projected that energy storage technologies will be the solution to the global energy demand especially during off-peak hours which will inspire industrial and economic growth globally.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

GGN performed writing of the original draft, writing, and editing, RBOO performed writing and editing, JKK conducted conceptualization, editing, and supervision. All the authors have read and approved the manuscript.

Acknowledgments

The authors are grateful to the Directorate of Research, Extension & Outreach, Egerton University, Njoro campus, for supporting this study.

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