Rechargeable Batteries: Technological Advancement, Challenges, Current and Emerging Applications

Abdul. Ghani. Olabi[1,2*] Qaisar. Abbas[1,3], Pragati A. Shinde [1], Mohammad Ali Abdelkareem[1,4]

[1] Sustainable Energy & Power Systems Research Centre, RISE, University of Sharjah, P.O. Box 27272, Sharjah, United Arab Emirates
[2] Mechanical Engineering and Design, Aston University, School of Engineering and Applied Science, Aston Triangle, Birmingham, B4 7ET, UK
[3] School of Computing, Engineering and Physical Sciences, University of the West of Scotland, Paisley PA1 2BE, UK
[4]Faculty of Engineering, Minia University, Egypt

Corresponding author: aolabi@sharjah.ac.ae

Abstract

Historically, technological advancements in rechargeable batteries have been accomplished through discoveries followed by development cycles and eventually through commercialisation. These scientific improvements have mainly been combination of unanticipated discoveries and experimental trial and error activities. However, with the increased complexity of rechargeable battery systems and diversification in ever-demanding new applications requires a strategical approaches to commercialise newly developed battery chemistries. This can only be achieved by fast-tracking the transfer of key finding from scientific laboratories to industrial collaborators in order to design commercially feasible devices. Despite the dominance of lithium-ion batteries (LiBs) commercially in current rechargeable battery market which ranges from small scale applications such as portable electronic devices to large scale applications including transportation to grid scale electrical energy storage. Scientific community is endeavouring to consolidate the global rechargeable battery portfolio with the alternative rechargeable battery systems based on cost-effective, safe, and environmentally friendly battery chemistries. This brief prospective will provide an update on the historical developments, current technological scenario and future expectations, current and potential applications, and challenges faced by current and future rechargeable battery technology.

Key words.

Renewable sources of energy, Rechargeable batteries, Technological evolution of batteries, Current and future applications

1. Introduction.

The development of energy storage and conversion systems including supercapacitors, rechargeable batteries (RBs), thermal energy storage devices, solar photovoltaics and fuel cells can assist in enhanced utilisation and commercialisation of sustainable and renewable energy generation sources effectively [1-4]. The deployment of these sustainable and renewable energy sources can bring in substantial socio-economic benefits together with constructive contribution towards sustainable and environmentally friendly development of human society [5-7]. The family of RBs particularly metal-ion batteries including widely used LiBs and other promising futuristics metal ion batteries such as zinc-ion, Mg-ion, Al-ion, and Na-ion batteries can play a vital role in the wider deployment of green sources of energy [8, 9]. Other types of RBs which are regarded as extremely promising candidate for future applications i.e., electric vehicles (EVs), hybrid electric vehicles (HEVs), emergency power backups and consumer electronic include metal air batteries and metal sulfur batteries. This is due to their relatively superior energy densities, higher power densities and longer cycle lives [10-12]. Amongst number of currently used batteries LiBs has unmatched performance characteristics such as superior energy density and power density when compared with other commercially utilised RBs as shown in **Figure 1.**

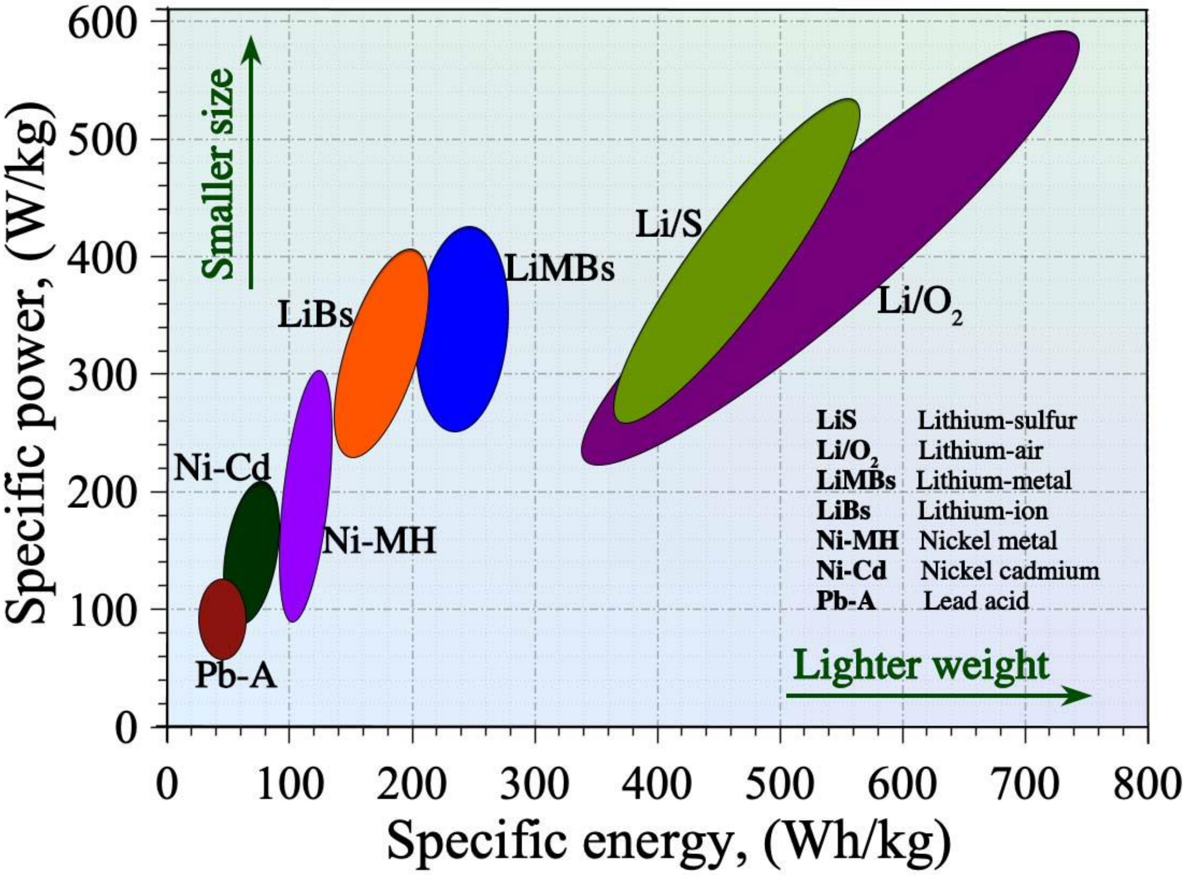

Figure 1: Graphical illustration of various rechargeable battery technologies in relation to their specific energy and power densities. The arrows specify the direction of improvement to decrease battery pack size and to reduce cell's overall weight.

Simplified comparison between various rechargeable battery systems is shown in **Figure 1** which are currently being deployed commercially or expected to be installed in near future. Superior characteristics of LiBs in comparison with other currently used battery systems make these batteries the technology of choice for wide ranging applications. Lithium sulfur and lithium air batteries have shown exceptional performance and are being considered as potential candidate for number of future applications. Increased demand of LiBs commercially in mid 80s resulted in attracting enormous research interest from both the government and private funding agencies alike resulting in swift technological development and enhanced commercial utilization of this technology. At present, key applications of LiBs include consumer electronics and EVs/HEVs whereas future applications may also include grid scale stationary energy storage using this technology [13-16]. However, it seems uncertain for LiBs to achieve future electrical energy storage demands in transportation and grid scale storage. There are two fundamental challenges i.e., the component's cost and safety concerns which may limit their use in these sectors. Even right now, LiBs can be expensive than some other battery technologies due to the limited availability and higher cost of lithium and other transition metal oxide-based components of Li-ion battery systems [17]. Increased demand of these battery systems in future especially in large scale applications can create the shortage of these components therefore increasing the production cost even further consequently, making this technology financially less viable [9, 18]. Second limitation for the adoption of these battery systems is their operational safety. Particularly, use of LiBs in EVs and smart phones has resulted in frequent fires and explosions lately which can restrict their wider use in these applications in future [19]. Even in normal operating conditions batteries can produces substantial amount of heat whereas in hot days or use of battery at higher temperatures can cause undesirable parasitic reaction which can result in thermal runaways or short circuiting of a battery cell [20]. Therefore, attention has been centred towards the development of next generation battery technology based on easily source-able raw materials and new/innovative cell designs making batteries of future more cost-effective and safer to operate under different conditions, respectively.

Lithium-ion batteries like any other rechargeable batteries have five key components i.e., anode, cathode, separator, electrolyte, and current collectors as shown in **Figure 2 (a).** Copper and aluminium are typically used as current collectors for anode and cathode respectively whereas carbon is used as anode and metal oxides as cathodes. Non-aqueous solutions such as $LiPF_6$, $LiCoO_2$ and $LiClO_4$ which contain lithium salts are employed as electrolytes [21]. Other anode materials include germanium-based materials, transition metal chalcogenides, silicon and metallic oxide which are also being used due to their unique physical and electrochemical properties [22-24]. Key parameter which can affect the Li-ion battery performance include the cathode particle size, diffusivity, and electrical conductivity and it has been observed that low diffusivity, larger particle size and higher cycling rate result in inferior performance [25]. Charge-discharge reaction for Li-ion batteries can be described using **Equations 1**, **2** and **3** when graphite and $LiCoO_2$ are used as negative and positive electrodes respectively [26].

$$\textit{Cathode:}\qquad \mathrm{LiCoO_2} \rightleftharpoons \mathrm{Li_{(1-x)}\,CoO_2} + \mathrm{XLi^+} + \mathrm{Xe^-} \qquad \mathbf{(1)}$$

$$\textit{Anode:}\qquad \mathrm{6C} + \mathrm{XLi_+} + \mathrm{Xe^-} \rightleftharpoons \mathrm{Li_x\,C_6} \qquad \mathbf{(2)}$$

$$\textit{Reaction}:\qquad \mathrm{LiCoO_2} + \mathrm{6C} \rightleftharpoons \mathrm{Li_{(1-x)}CoO_2} + \mathrm{Li_x\,C_6} \qquad \mathbf{(3)}$$

Even though LiBs have been used on large scale in commercial applications however, newly emerging applications of Li-ion batteries in transportation and grid-scale storage require even higher energy densities (> 500 Wh/kg at cell level). To attain this level of performance thick electrode design has been adopted at reasonably low cost (< $ 100/kWh at pack level) [27] which has resulted in increased volume ratio of active materials as shown in **Figure 2 (b)**. Li-ion batteries have provided a foothold in EVs/HEVs in small and medium transport vehicles segment however due to its performance limitations, safety/environmental concerns and associated production cost which are consider key disadvantages has urged scientist to find suitable alternatives for future applications. Magnesium ion (Mg-ion) batteries can be appropriate substitute since these are safer to use as magnesium has a melting point of 660 ℃ when compared with 185.5 ℃ for lithium. It is also cost-effective to produce Mg-ion batteries since magnesium is second most abundant and inexpensive element [28]. Furthermore, magnesium is environmentally friendly and production processes involved for the manufacturing of Mg-ion batteries are environmentally less harmful and are not as energy intensive. Finally, magnesium has higher theoretical volumetric capacity of 3833 mAh cm^{-3} as compared to 2262 mAh cm^{-3} for lithium at fraction of cost since magnesium cost 4600 US $ per ton as compared to 165000 US $ per ton for lithium [29]. Structural design and operating principle of Mg-ion batteries is similar to that of Li-ion batteries as shown schematically in **Figure 2 (c)** and given by **Equations (4)** and **(5)**.

$$\textit{Anode: } \mathrm{xMg} \rightarrow \mathrm{xMg}^{2+} + 2\mathrm{xe}^{-} \qquad \textbf{(4)}$$

$$\textit{Cathode: } \mathrm{xMg}^{2+}\ 2\mathrm{xe}^{-} + \mathrm{V}_2\,\mathrm{O}_2 \rightarrow \mathrm{Mgx}\,\mathrm{V}_2\mathrm{O}_5 \qquad \textbf{(5)}$$

Even though, Mg-ion batteries possess an immense potential for future applications, these batteries are still at an early stage of development and face number of key challenges to make this technology a success similar to that of Li-ion batteries. Firstly, overly complex reaction chemistry necessitating further studies to understand the underpinning chemistry. Secondly, sluggish reaction kinetics due to the continuous deposition of Mg^{2+} ions on the electrode surfaces resulting in blockage of diffusion channels giving rise to inferior cycling. This can be due to the absence of stable and efficient cathode materials which can assist in addressing the sluggish nature of electrochemical reaction. Finally, suitable electrolytes which are compatible with electrode materials. Other common factors which can affect the performance of Mg-ion batteries include the ionic diffusion which can be addressed through the introduction of tuneable porous structure. Also, preintercalation and modification in chemical composition can also improve the reaction kinetics therefore overall cell performance.

Similar to other rechargeable batteries, aluminium-ion (Al-ion) batteries work on the fundamental principle where energy is stored with the movement of Al ions from anode to cathode. On recharging, Al ions return back to anode with the release of three electrons as shown in **Figure 2 (d)**. This anodic and cathodic reaction can be represented by the following half reaction using **Equations (6)** and **(7)** [30].

$$\textit{Anode: } 4\mathrm{Al_2Cl_7^-} + 3\mathrm{e^-} \rightleftharpoons 7\mathrm{AlCl_4^-} + \mathrm{Al} \qquad \mathbf{(6)}$$

$$\textit{Cathode: } \mathrm{xC} + \mathrm{AlCl_4^-} \rightleftharpoons \mathrm{C_x}\,(\mathrm{AlCl_4^-}) + \mathrm{e^-} \qquad \mathbf{(7)}$$

Although pace of research has really picked up after 2010 in the field of Al-ion batteries since Al-ion batteries can offer nearly four folds higher volumetric capacity theoretically and aluminium can be sourced cost-effective as there is a mature infrastructure in place to produce and recycle aluminium [31]. However, there are number of key challenges remained unresolved to makes this technology suitable for use at industrial scale, particularly in automotive industry. The main challenge is to find suitable electrolytes which are compatible with other battery components.

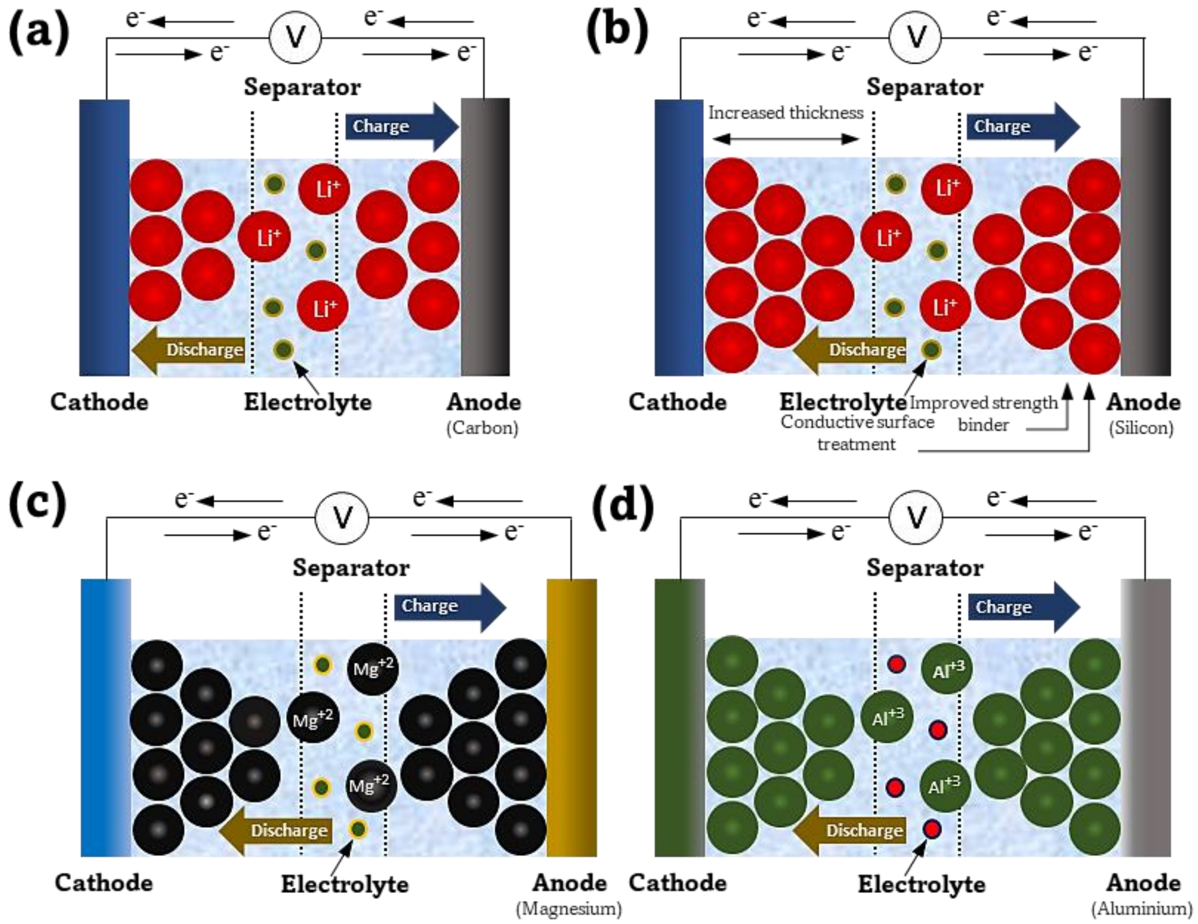

Figure 2: (a) typical battery configuration of LIBs **(b)** new and improved battery setup of LIBs for electric vehicles **(c)** graphical representation of a typical Mg-ion battery cell **(d)** graphical design of an Al-ion battery cell.

2. Historical development of rechargeable batteries.

Batteries are by far the most effective and frequently used technology to store electrical energy ranging from small size watch battery (primary battery) to megawatts grid scale enenrgy storage units (secondry or rechargeable battery). Term battery was first introduced by an american scientist Banjamin Frankline in 1748 when he built a multi-plate capcitor and named it as ‘‘electrical battery’’ [32]. Whereas, first proper battery cell was designed by Alessandro Volta in 1800 where zinc and copper electreodes were separated by cardboards and brine solution was used as an electrolyte which is still the template for modern day battery cell. This cell later evolved into Daniel cell and Leclanche cell in 1836 and 1866 respectively [33]. Lead-acid battery was the first device considered a truly operational aqueous rechargable battery made by french scientist Gaston Plante in 1859 which still retains fair share of battery market even today [34]. This battery was designed with the Pb || H_2SO_4 || PbO_2 configuration where on discharging the battery cell, PbO_2 is reduced to form $PbSO_4$ at positive electrode whereas negative electrode is oxidised to form $PbSO_4$ simultaneously. On recharging, the battery systems returns to its intial stage to complete the charge/discharge cycle [35]. Invention of lead-acid battery was soon followed by the development of nickel-cadmium battery by swedish scientist Waldemar Junger in 1899 [36]. Nickel-cadmium batteries were later redesigned and improved by Neumann in 1947 where he succeeded in producing a sealed battery cell by re-combining gases from the reaction of battery components which is the current design of nickel cadmium batteries [37]. Also, by early twentieth century, new battery was deemed necessary to increase the electrical effeciency, enhance cell life time, reduce cost and increase energy density especially to use it in newly evolving auto industry. Edison manged to design rechargeable battery with such charecteristics and sucessfully used it in automotives with an average covered distance of 144.35 miles on a signle charge [38]. Nevertheless, rechargeable battery technology which truly revolutionised electrical energy storage came with the introduction of LiBs at commerical scale in early 90s on the back of research drive started in early 1970s by M.S Whittingham and later enhanced in mid 1980s by John B. Goodenough. Devlopment and introduction of LiBs resulted in increasing the enenrgy density nearly five folds when compared with previous batteries employing less efficient electrode materials i.e., lead, nickel, cadmium based batteries [39, 40]. Untill reecently, most technological development in LiBs has been focused towards small scale applications such as portable electronics, back up systems and medical equipment. However, now focus tends to be shifting towards medium and large-scale applications such as EVs/HEVs and grids size stationary applications due to increased awareness of global woarming and the danger to environment. Historical evolution and technical progression in battery technology over past three centuries is presented graphically in **Figure 3**.

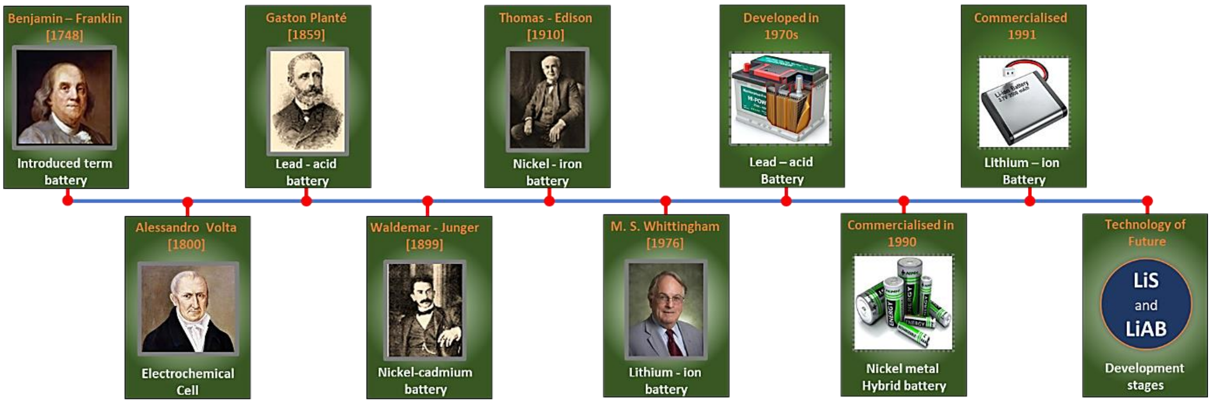

Figure 3: Historical evolution of battery technology from mid-18th century to date [32-34, 38, 39, 41].

It does not seems over yet for LiBs, as further devlopment of these batteries can boost their performance even further however this enhcement in performance seems to be incremental and execpted to add an addiotnal 30% in energy density of LiBs [42]. This enhancement can be anticipated by replacing the liquid electrolyte solutions with solid electrolytes enabling the battery to store enough energy to propel vehicles with similar range as gas powered cars. However, with the technoligical development reaching its saturation point and increased cost of LiBs has forced researchers to investiagte new battery chemistries such as lithium sulfur and lithium air to improve energy densities and safety of rechargable batteries based on current technology for future applications. Lithium sulfur and lithium air batteries have much higher theoratical energy and power desnties as shown in **Figure 1**. However, compared to Li-ion batteries, Li-S batteries are more prone to security issuess and have a lower working voltage. Due to "Shuttle effect", cycling performance is also poorer. Similarly lithium air batteries do have some critical issues to be adddressed such as low round trip effeciency, air purification and low practical air capcity prior to its use commercially. This enhancement in performance is expected to be achieved through the understaing and improvement of battery chemistry and by using better designed electrode materials, electrolytes and cell structures.

3. Present technological state and future development direction of rechargeable batteries.

Currently, number of RBs ranging from Pb-acid battery to Li-ion battery are being utilized in diverse range of commercial applications. Pb-acid battery is the oldest and very first battery technology to be used commercially. Due to its low components cost and well established battery chemistry, it still accounted for more than 50% of secondary battery market share in 2015 however Pb-acid batteries suffer from inferior energy densities ∼35 – 40 Wh kg^{-1}, short cycle life and toxicity of raw materials [43]. In contrast, nickel iron (Ni-Fe) batteries has 1.5 – 2 times energy densities and much longer cycle life of >2,000 cycles at 80% depth of discharge which is much higher than other battery technologies of same era such as 300 – 400 cycles for Pb-acid, 500 – 800 for Ni-MH and 1300 – 1600 for Ni-Cd [44, 45]. However, all these battery systems struggle to compete with the overall superior performance of LiBs. **Table 1** provides a performance comparison of different rechargeable battery technologies currently being used commercially.

Table 1: Performance characteristics of different rechargeable battery systems.

Battery type	**Cycle life**	**Energy density** (Wh kg^{-1})	**Efficiency** (%)	**Working voltage** (V)	**Operating temperature** (°C)	**Self-discharge** (%)	**Ref:**
Li – ion	1,000	200	Up to 99	4 – 5.3	−20 – 60	Up to 44	[46-51]
Ni – Fe	2,000	100	91	Up – 1.7	40	Up to 30	[45, 52-56]
Pb – acid	200	30 – 50	75 – 80	12 – 42	~ 25	5 – 10	[44, 57-62]
Ni – MH	500 – 800	40 – 110	70 – 90	6 – 9.78	15 to 35	-20 – 45	[44, 63-67]
Ni – Cd	2000 – 2500	50 – 75	75 – 85	1.2 – 1.45	10 – 40	10	[44, 68-73]

Inherent limitations and inferior performance properties of these systems as given in **Table 1** coupled with rapid technological development of LiBs making these LiBs market leader in RBs segment. LiBs are currently the technology of choice for wide range of applications and expected to remain very useful technology for near to mid-term future due to their excellent all-round performance.

Metal air batteries (MABs) have also attracted significant focus recently since these are considered another class of electrochemical devices having immense potential as next generation high energy density RBs. MABs work through oxygen reduction and metal oxidation providing them with huge advantage of theoretical capacity 3-30 times higher than currently used LiBs [42]. Li-air and Zn-air are the two front running technologies however Al-air and Na-air have also seen considerable interest lately. Li-air and Zn-air are preferred due to their superior theoretical energy densities of 11,429 W h kg^{-1} (based on the mass of Li metal) and 1,350 W h kg^{-1} (based on the mass of Zn metal) respectively [74]. Similar to other RBs, work on flexible and solid state MABs is also underway to bring MABs technology in line with other mainstream rechargeable battery systems. However, MABs do suffer from inferior power density and unsatisfying Coulombic/round trip efficiencies necessitating attention. Metal sulfur batteries have also attracted increased consideration recently due to the success of lithium-sulfur (LiS) batteries which are now approaching the pragmatic applications stage. Battery chemistries based on Na-S, Ca-S Al-S, Mg-S and K-S are gaining prominence since their battery components are much cheaper and cells are safer to operate due to multivalent metal-sulfur systems [75]. Furthermore, metal- sulfur batteries can offer improved volumetric energy densities since sulfur contains higher theoretical storge capacity 1675 mA hg^{-1} which is ≈ 10 times higher than cathodes of Li^{+} metal. Additionally, cost of sulfur (\$150 ton^{-1}) is nearly 2 orders of magnitude lower than that of $LiCoO_2$ (\$10 000 ton^{-1}) [76]. Number of key research challenges such as the high reactivity of metallic anodes e.g., Li, Na, Mg, & Al and the solubility of sulfur species in the electrolyte are outstanding issues requiring further development work of metal-sulfur batteries [77].

Therefor it can be established that battery systems which can be prospective candidates for future applications are mainly multivalent ion metal anode based RBs with the potential to deliver high energy densities [78]. However, these technologies based on Mg, Ca, Al, and Na are at different level of maturity necessitating enormous amount of investigative work to bring these technologies to wider industrial scale applications. Sodium and magnesium-ion based batteries are the most promising battery technologies which can play a key role in future electrical energy storage applications. Na-ion batteries benefit from similar electrochemistry as LiBs but at reduced cost. However, larger Na^{+} ion size exert higher strains on the host lattice resulting in pulverization due to volume changes during cycling. New techniques to address this issue are necessary for long terms commercial suitability of Na-ion batteries. On the other hand, magnesium ion batteries have dramatically different electrochemistry with much superior theoretical capacity thanks to the advantages of the divalent ions. However, sourcing of high performance cathode materials for magnesium ion batteries is going to be the major breakthrough of the future if this technology has to see commercial applications [79]. There are two major current and prospective markets for these existing and next generation of rechargeable batteries i.e., EVs/HEVs and grid scale energy storage which are currently operated using fossil fuels such as oil, natural gas, and coal. In order to compete with energy produced from fossil fuels, RBs have to improve on at least these three major requirements i.e., cost, performance, and safety. Environmentally friendly and cost-effective materials are highly desirable as battery components i.e., sodium can be preferred over lithium due to its lower cost and environmentally friendly nature however Na-ion batteries have limited cathode options when compared with LiBs which will see broadening in due course thanks to the amount of research being carried out in this area. In order to achieve cost parity such as in case of gasoline driven vehicles, deployment of more cost-effective battery systems such as Na-ion and solid-state devices seems inevitable. Cost reduction in battery production can be achieved using three different strategies i.e., reducing the components cost (substituting the costly materials such as lithium with cost-effective sodium), economy of scale (gigafactories) and enhancing cell performance (reducing the number of cells in a battery stock). Current drop in cost has been achieved by bringing LiBs below the parity line of \$100/kWh through performance enhancement and economy of scale. However to improve the cost-effectiveness even further, will only be possible by using different battery chemistries, cost effective components, increasing cell life and through cell management [80]. Safety, recycling and environmentally friendliness of these RBs are also becoming increasingly important during the selection process of these electrochemical energy storage device. These issues will be discussed briefly in the following sub-section.

Safety of RBs (during storage, transportation, operations, and recycling) are of immense importance. Even though number of incidents of safety breaches have been low e.g., since the early commercialisation, some 153 incidents have been recoded for all type of batteries by Federal Aviation Administration (FAA) USA where nearly 50% of the incidents involved lithium-based battery systems, however these have still drawn huge media attention and resulted in recalls from manufacturers [81]. Usually, it has been argued that organic electrolytes and flammable nature of lithium are main causes for the inadequate safety of rechargeable batteries when used in higher temperatures or in the form of large stocks of battery cells. Different solutions have been proposed to address these concerns including using aqueous/ionic liquid electrolytes, producing solid state devices and implementing thermal management systems [82]. However, achieving expected performance using these electrolytes is still a challenge. Furthermore, volume changes during charge-discharge cycles especially for solid-state batteries across electrode-electrolyte interface still demand attention. Alternative active materials such sodium have also been suggested to substitute lithium however the development of Na-ion batteries is still at it infancy stage requiring more time before these can be commercialised. Furthermore, Na can react more easily in air when compared with lithium and result in forming Na_2O [83, 84].

Recycling of RBs is becoming ever imperative due to their intensive use in portable electronics and transportation applications which has resulted in producing vast quantities of spent battery components [85]. This has diverted researchers and commercial vendors attention to explore more facile and highly efficient recycling processes in order to fulfil the strict environmental regulations and achieve resource conservation. However, recycling of RBs is an extremely complex process because of elemental diversity and composition complexity [86]. Pb-acid batteries have well established recycling procedures due to technical maturity and simplicity of design whereas other RBs such as Li-ion, Ni-MH and Ni-Cd are not recycled to great extent due to the complexity of design and contents [87]. Hydrometallurgical and pyrometallurgical processes are two basic methods used to recycle RBs, both these techniques are very complicated and can produce secondary pollution in the form of gasses, wastewater, noise pollution and other residues. These harmful emissions should be prevented in order to achieve zero emission from secondary pollution originating form recycling of rechargeable batteries.

Environmentally friendliness of RBs can be enhanced using number of different strategies such as by developing more effective manufacturing processes to improve energy efficiency, reduce the heavy metal portion of electrode active materials, and by selecting more environmentally friendly electrolyte solutions and binders which will subsequently lessen the environmental impact of RBs. RBs environmentally friendliness can also be improved by substituting toxic battery components with less or non-toxic ones or by exploring less energy intensive production and recycling technologies.

4. Current and emerging applications of rechargeable batteries.

At present, RBs perform a crucial role in the progress of highly capable as well as multipurpose energy storage technologies in ensuring worldwide switch over from traditional fossil fuels to the renewable energy resources [88]. RBs are extensively used in commercial markets, which are constantly advancing human lives by offering plenty of benefits keeping together the necessities and luxuries of modern time [89]. RBs have become the key source of carbon-free transportation in automobile industry (Electric-mobility) and energy segment such as stationary energy storage applications. Batteries have long list of applications ranging from running apps on cell phones to life-saving medical devices, wearable electronics, aerospace, electric vehicles, robotics and power grids [90]. RBs are also widely utilized for large scale power grid storage for energy generated through renewable sources such as solar, wind, tidal and geothermal. Presently, RBs are frontrunners of current market in various fields and make human lives more innovative via development of new products and their introduction to the commercial market. Number of current and anticipated applications of RBs are presented schematically in **Figure 4**.

Figure 4: Schematic interpretation indicating opportunities of batteries in commercial market.

Following the epidemic of shortage of oil and the effect of greenhouse gaseous coming out of conventional combustion engine-based vehicles, researchers around the globe began to work on eco- friendly vehicles form early 70s which can rely on alternative source of energy. The best answer to these challenges is the currently growing electric vehicles (EVs)/hybrid electric vehicles (HEVs) market which can have huge influence in our daily lives as these can meet our needs by providing a great prospect of transport, communication, and surveillance with insignificant environmental impact [91]. RBs perform a fundamental role in the industry of EVs, as these are crucial source of electricity for EVs to power up electric motor. LiBs are one of the most widely used batteries today for EVs as these have significant weight advantage over other battery systems and many other features including high energy density, long cycle life and high efficiency [92]. Batteries for EVs require high energy storage capability in order to deliver power to motor which can drive for prolonged period of times other than for start-up and lighting [93]. Moreover, electric mobility is one of the major industry that uses rechargeable battery as a source of electricity to power up electric motor [94]. Electric mobility comprises all the automotive vehicles which uses either entirely electric motor (EVs) or vehicles that uses small combustion engine and electric motor (Range Extended EVs) and vehicles which combines traditional internal combustion engine and electric propulsion system (Hybrid Electric Vehicles or HEVs). These vehicles use electricity from batteries to power their motors impeding the production of toxic gases produced from the combustion of fossil fuels inside the internal combustion engines [95]. Recently, market for stationary energy storage (wind and solar) have also undergone incredible growth because of the encouraging government incentives like renewable portfolio standards coupled with remarkable decrease in technology expenditures. Encouraged from the current technology and production cost, the cost of solar photovoltaics (PV) panels was reduced by nearly 89% from 2010 levels which is estimated to drop further by 34% before 2030 [96]. The conventional PV panels simply covert solar energy into electricity for its instant direct use, however these do not have any storage capabilities. RBs are employed successfully for solar energy storage along with PV panels because of their light weights, minimum maintenance and scalability [97]. Batteries assist in converting electric energy into chemical energy thus performing green transfer/storage of electric energy into chemical energy and conversion of chemical energy into electrical when needed [98]. These are the four key battery technologies used for solar energy storage, i.e., Li-ion, lead-acid, nickel-based (nickel-cadmium, nickel-metal-hydride) and hybrid-flow batteries.

We also depend strongly on RBs for the smooth running of various portable devices every day. RBs are vital for powering devices such as remote controls, cell phones, smart watches, digital cameras, laptops, torches, and many other devices [99]. LiBs are lighter than other battery systems such as lead-acid batteries therefore being used as portable power banks. RBs can bear movement and temperature changes therefore maintain their power output during extreme operational conditions [100] making batteries economical and robust in challenging environments. LiBs are also extensively used in power backups or UPS systems as an emergency source to protect these systems from usual power failure or voltage fluctuations. Batteries are different from the traditional generator power supply in the sense that these can provide instant power to connected equipment. Various health equipment's such as insulin pumps, hearing aids, artificial limbs and regulator valve assisted devices also utilise RBs. Moreover, batteries are extensively used in other medical instruments. Electrocardiogram (ECG) monitor is always attached to the battery as it can be moved with the patients requirement, and it needs switched on all the time. Batteries such as Li-ion and Ni-Cd are commonly used in hospitals [101]. Furthermore, Heavyweight batteries are mainly used in construction and logistics. These are used to power machineries like forklifts otherwise carbon monoxide and toxic gases produced during combustion is hazardous in such workplaces. Batteries are perfect for remote monitoring gadgets too. These are employed in radios, where emergency response is required in military operations for communication. Additionally, the surveillance and alarm systems which protect our lives everyday are also powered by Li-ion batteries.

RBs are considered the most popular electrical energy storage devices currently available where these are employed in large scale in industries ranging from aeronautics to telecommunication, automotive, information technology and portable electronic devices. Therefore, it can be concluded from the above discussion where wide range of applications of RBs have been explored briefly, batteries are the right choice that makes our life more interesting, innovative, and safer, if the concerns about their operational safety and environmental impacts are addressed appropriately.

5. Conclusions.

Modern-day battery technology has come a long way with the development spanning over hundreds years, essentially making battery technology part of our everyday lives. However, understanding of underlying fundamentals of battery chemistry has been understood in past few decades. This has provided electrochemist with the fundamental tools to develop battery chemistries of future and enhance performance of these battery systems even further to keep up with new and novel applications emerging on regular basis. To keep up with the introduction of new applications in the fields of transportation, communication, medical, aerospace, grid scale energy storage and portable electronics, new and innovative strategies for the development of new batteries systems are vital. These new devices believed to result in enhanced performance i.e., energy densities, cycling, power capabilities and efficiencies. Other factors require considerations include operational safety, environmentally friendliness, sustainability of sourcing of battery components and end of life consideration i.e., reusing and recycling. This can only be achieved by using new and integrated methodology away from Edisonian approach based on step-by-step progression. These strategies will be responsible to meet the current energy storage needs and develop new concepts to fulfil the electrical energy storage requirements for years to come.

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