
Energy: Rechargeable Batteries and Sustainable Development

Dr. Santosh Kumar

F. Y. B.Tech Department
G.H Raisoni College of
Engineering and Management
Pune, India

Ms. Shubhangi Satdeve

F. Y. B.Tech Department
G.H Raisoni College of
Engineering and Management
Pune, India

Mr. Yash A. Zode

Computer Department
G.H Raisoni College of
Engineering and Management
Pune, India

Abstract— Electrical energy storage technologies play a significant role in the demand for green and sustainable energy. Rechargeable Batteries or secondary batteries, such as Li-ion batteries, Na-ion batteries, and Mg-ion batteries, reversibly convert between electrical and chemical energy via redox reactions, thus storing the energy as chemical potential in their electrodes. Li-ion batteries to hold more energy than other conventional batteries is what has kept it at the top of the battery pyramid for more than a decade. . However, to create a more sustainable future, scientists and engineers have continued to search for a battery technology that could one day replace the Li-ion and solve its many limitations. Lithium – ion rechargeable battery has a great output for powering many of our day to day energy requirements.

Index Terms— Sustainable Energy, Rechargeable Batteries, Redox Reactions, Conventional Batteries

INTRODUCTION

In addition to the rising concern of environmental pollution, modern society is becoming increasingly dependent on uninterrupted portable power sources for continuous Internet access and for working or collaborating with people across the globe. In spite of the efforts of both the research community and industries, the development of portable power devices has been painstakingly slow [1, 2] falling behind the rapid advancements in electronic devices and electrically powered instruments and infrastructure. The industrial revolutions in the past centuries have led to unprecedented changes in social life, transportation, and production activities, with energy utilization reflecting the progress of industrial technology and human civilization. Fossil fuels, such as coal, crude oil, and natural gas, are used as primary energy sources to power all high-tech dependent human activities. However,

pollution arising from fossil fuel combustion has had a devastating impact on human health and the natural environment [3, 4]. In addition, regardless of governmental policies or the fluctuation in price and supply, the natural reserves of fossil fuels are limited and not sustainable. Therefore, the focus of research has shifted to environmentally benign sustainable energy. Clean energy can be divided into three components: harvest and conversion of sustainable clean energy including solar energy, wind, mechanical vibration, and waste heat; energy storage typically in the form of chemical potential including batteries, hydrogen, and biofuels; and management and efficient usage of energy including smart buildings and efficient lighting systems [5–10] (Fig. 1). Typical energy storage technologies, particularly for portable electronics and mobile instruments, are based on the conversion of electricity and chemical potential, as seen in fuel cells, batteries, and electrochemical pseudo capacitors, with the energy being stored in the form of chemical potential [6, 11–13]. Due to their high energy density, batteries have long been used [14] to power portable electronics, as well as stationary and mobile instruments [15], such as lead acid batteries for automobiles [16]. In the last two decades, Li-ion batteries have advanced rapidly with increased energy density and long cyclic stability, which is beneficial for most portable electronics including mobile phones and laptop computers [16–19]. Currently more studied have been required for academia and industry to focus on today's batteries which are depend on ion inclusion / removal in batteries and electrodes, including Li- [20–22], Na- [23–25], Mg- [18,26,27] and Al-ion [28,29]. However, Li has shown more reducing and gravimetric property than Na, Mg, and Al [reducing power: Li (3.04 V), Na

(2.71 V), Mg (2.37 V) and Al (1.66 V); gravimetric capacity: Li (3850 mAh/g), Al (2978 mAh/g), Mg (2046) and Na (1165)]. Thus, devices based on metallic sodium, magnesium, or aluminum anodes have lower energy densities and operating voltages than those with lithium metal anodes [25, 26, 28]. To date, only Li-ion rechargeable batteries have been successfully commercialized and become an irreplaceable power source. In Li-ion rechargeable batteries, the cathodes that store lithium ions via electrochemical intercalation must contain suitable lattice sites or spaces to store and release working ions reversibly. Robust crystal structures with sufficient storing sites are required to produce a material with stable cyclability and high specific capacity [24, 30]. In addition, a cathode with high electro-chemical intercalation potential can be used to develop a high energy density battery with a given anode. This is because the energy density of the device equals the product of the specific capacity of the electrode materials and the working voltage that is determined by the differential electrochemical potentials between the cathode and anode [22, 31]. This review focuses on secondary Li-ion batteries and their components to illustrate certain fundamental factors, in particular, the origin of the electrochemical potential of electrode materials and effective approaches to exploiting these electrochemical properties. In addition, the potential electrode materials for Na- and Mg-ion batteries are also discussed as the fundamental understanding acquired on Li-ion batteries will greatly benefit the increasing efforts on Na- and Mg-ion battery research [32].

The energy utilization chain. Efficient harvest, storage, and management are three essential segments to energy consumption in modern society [5, 33].

Configuration and principle of Li-ion batteries

Li-ion is a rechargeable battery immersed in an electrolyte having internal connection by a polymer membrane and two electrodes anode and cathode (Fig. 2). This basic device configuration has remained unchanged from the earliest developed batteries [34]. The similarities between Li-ion batteries and conventional batteries include the redox reactions at the interfaces between the electrolyte and electrodes, accompanied by the diffusion of ions in the electrolyte. However, the differences between conventional batteries, or galvanic cells, and Li-ion batteries are notable as well. In typical galvanic batteries, the redox reactions proceed simultaneously with the receding or advancing of the electrode surfaces, but not accompanied by either the solid-state mass diffusion in the electrodes or a change in the chemical composition and local atomic environment [35]. By contrast, the heterogeneous redox reactions in Li-ion batteries are always accompanied by solid-state mass diffusion as well as volume expansion or contraction, although the electrode surfaces do not recede or advance when the volume change of electrodes is not considered. Therefore, it is very reasonable that researchers face different challenges when developing Li-ion batteries, necessitating different fundamental considerations. The working of Li ions as an electrochemical reaction is through the electrolyte and anode and cathode.

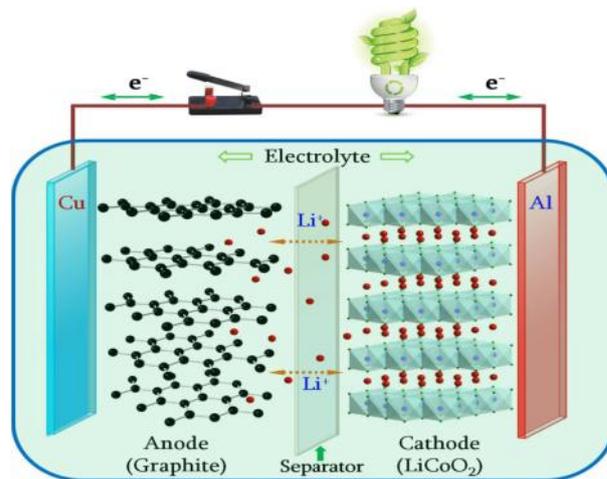
FIGURE 1



The storage of lithium ions in electrodes occurs via three types of electrochemical reactions: (1) alloying such as silicon and tin [36–38]; (2) conversion such as CuO and SnO₂ [39]; and (3) intercalation such as graphite, LiCoO₂, and V₂O₅ [39–41]. Conversion reactions are often limited by their irreversibility, thus requiring small particle sizes, typically less than 20 nm in diameter [42]. Therefore, conversion reactions are often combined with alloying [21], but they are rarely used alone in lithium-ion batteries. The compounds most commonly studied and widely used for Li-ion intercalation are transition metal-containing

compounds with layered, spinel, or olivine structures [30, 48]. The cathode, anode, and electrolyte are the most important active materials that determine the performance of a Li-ion battery. As anode materials offer a higher Li-ion storage capacity than cathodes do, the cathode material is the limiting factor in the performance of Li-ion batteries [1, 41]. The storage of Li-ion battery totally depends upon its density and potential of cell. Li-ion storage is due to employability of electrode for valence state change, free state for accommodation to Li-ions and reversibility of reactions. Although batteries offer a much higher energy density than electric double-layer capacitors (EDLCs), also often referred to as super capacitors or ultra capacitors, and electrochemical pseudo capacitors, they possess relatively lower power density and shorter cyclic life [11,52]. A significant number of studies have been conducted on the synthesis and characterization of various nano structured cathode and anode materials with large specific surface area and short solid-state transport distance, offering an enhanced power density as well as a better cyclic stability [53, 54]. The energy storage performance has been enhanced by conformally applying a thin (typically a couple of nanometers) and porous carbon film (with a pore size of a few nanometers or less) on nano structured cathode or anode materials [55-57]. A high power density can also be obtained by fabricating hybrid super-capacitor batteries [51, 62]. However, enhancement of the energy density in a battery is limited by the lithium-ion storage capacity and the cell potential. The storage capacity is determined by the amount of lithium ions that can be reversibly inserted and extracted through a reversible first-order phase transition in intercalation reactions under the operating conditions of the battery [63, 64]. The electrochemical potential varies with the materials in question, showing a direct correlation with their electronic configuration. Electrode materials have been selected w.r.to properties like stability, capability and efforts regarding research [65-69]. However, experimental studies on controlling and tuning the electrochemical potentials of electrode materials are limited, although some notable theoretical studies have calculated and analyzed electrochemical potentials based on the electronic structure and atomistic potentials [50].

FIGURE 2

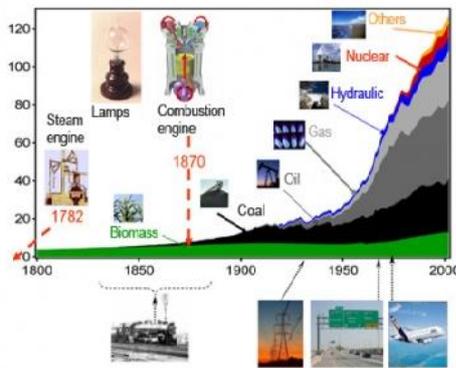


Schematic of the configuration of rechargeable Li-ion batteries. Na-ion, Mg-ion, or Al-ion batteries also have similar configurations, which differ from electrode materials [29, 70, and 71]. For a Li-ion battery, as illustrated in the figure, Li ions are extracted from the cathode and inserted into the anode during the charge process, and the reverse reaction occurs during the discharge process. However, in a half-cell consisting of electrode material and lithium metal, Li ions are extracted from the electrode material and deposited on the surface of the lithium metal during the charge process, and Li ions are inserted into the host electrode material during discharge. Here, in practice, the electrode materials can be cathodes or anodes.

Current and future energy context

Our growing dependence on energy is linked to eighteenth century discoveries and the technologies that ensued (Fig. 3). Human beings originally relied on biomass as their sole source of energy, without this impacting on the environment since plants reabsorbed the CO₂ released, through photosynthesis. This situation endured until the end of the 18th century, when James Watt invented the steam engine. It was the first machine able to transform thermal energy into mechanical energy, marking the start of the first industrial revolution with the appearance, amongst other things, of steam trains.

FIGURE 3



The nineteenth-century discoveries that led to twentieth-century technologies are presented with the evolution over time of the different sources of primary energy used: first renewable energies, then non-renewable ones.

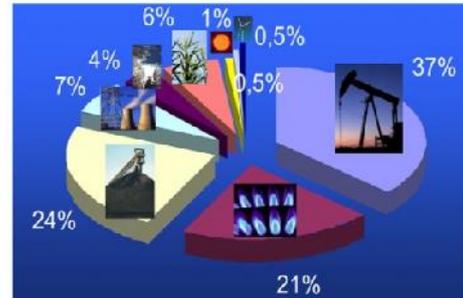
From Jean-Marie Martin-Amouroux, IEPE, Grenoble, France, and a presentation by K. Harriet, DOE.

Industrialization further intensified at the end of the nineteenth century, particularly with the discoveries of the internal combustion engine (by Etienne Lenoir) and of electricity, which led to our growing dependence on fossil fuels. The arrival of new transport technologies and other nineteenth-century advances only further increased our total energy consumption, which has become gigantic, in excess of 1.2×10^{14} kWh/year, corresponding to an installed capacity of the order of 14 tera-Watts (14×10^{12} W).

Energy efficiency, which is often very low in many uses, is a parameter that needs to be taken into consideration. As an example, for 2 joules of light energy supplied by an incandescent lamp, we need 100 joules of primary energy, with 98 joules consumed by the thermoelectric conversion and by distribution. Hence the importance of avoiding, as much as possible, thermoelectric type conversions, given the limitation imposed by Carnot's principle.

Eighty two percent of the primary energy used worldwide comes from fossil fuels (coal, gas, and oil); the rest comes from renewable energy (sun, wind, sea, and others) and nuclear energy – 11% and 7% respectively.

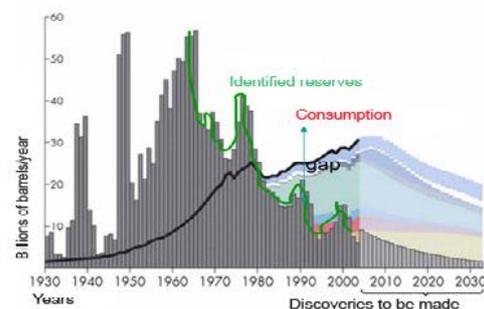
FIGURE 4



Distribution of primary energy sources used worldwide in 2010. Non-renewable, renewable and nuclear energies represent 82, 11 and 7% respectively.

Fossil fuels are not inexhaustible and several models, based on estimates of the growth of current consumption and the reduction of identified reserves, predict that remaining oil, gas, uranium, and coal reserves will only last 41, 62, 64 and 230 years respectively (Fig. 3). Even if these estimates are not exact, note that a mistake of 100 billion tons of oil reserves would only shift the timeframe by +/- 10 years. In the space of one or two centuries, we will therefore have used up the fossil reserves that took millions of years to accumulate on our planet. This catastrophic scenario had been announced as early as 1956 by the US geophysicist M. King Hubbert¹, but kept silent until the first oil crisis in the United States in 1970.

Figure 3



Growing gap between our planet's energy demands and proven or still undiscovered fossil fuel reserves, which are diminishing.

The sectors of primary energy consumption are transport, industry and habitation, accounting for 23, 24 and 42% respectively, with the remaining 11% lost in distribution. Knowing that a litre of gasoline releases 2.5 kg or 1,200 L of CO₂, the

transport domain is responsible for 30% of the 26 Gt/year of CO₂ currently emitted, which have contributed to the rise in atmospheric carbon concentration from 250 ppm in 1950 to 370 ppm in 2010 and 405 ppm in 2017

Even though other factors, like solar activity, contribute to these high carbon emissions, the latter undeniably influence the Earth's evolution, both in terms of the level of global warming and of the rise in sea levels, since the two are correlated through a simple expansion effect. Here again, while we seem surprised by these phenomena, some of our predecessors such as Joseph Fourier in 1800 and Swedish chemist Swante Arrhenius in 1850, had foreseen and even calculated a rise in our planet's global temperature due to an increase in the atmospheric carbon concentration.

This global warming translates into the disappearance of certain glaciers, the acidification of oceans (demonstrated by coral bleaching), melting ice caps, the rise in sea level (which is a threat to certain islands like those of the Maldives archipelago) and growing damage caused by storms and floods, to name but a few. In a few decades, climate change could completely reconfigure our geography and cause us to relocate industrial and agricultural areas. This situation is also aggravated by the demographic component, judging from the continuous growth of the population which will rise from 6.5 billion to 9 billion in 2050, as well as the ever growing consumption per capita – which puts estimates for the available power necessary for global consumption in 2050 at 28 TW. As a result, if we maintain the “laissez-faire” policy of energy production and use, we will emit 55 Gt CO₂ in 2050 and 75 Gt in 2100, which corresponds to carbon concentrations of 500 to 700 ppm. All models, however conservative, indicate that such concentrations would lead to temperature increases of 2°C (at least) in 2100, which would lead to a 30 cm rise in sea levels.

References:

- [1] J.M. Tarascon, M. Armand, *Nature* 414 (6861) (2001) 359.
- [2] J.B. Goodenough, Y. Kim, *Chem. Mater.* 22 (3) (2010) 587.
- [3] IEA, *Transport Energy and CO₂: Moving toward Sustainability*, International Energy Agency (IEA), Paris, France, 2009.
- [4] X. Yin, et al. *Energy Policy* 82 (0) (2015) 233.
- [5] Q.F. Zhang, et al. *Chem. Soc. Rev.* 42 (7) (2013) 3127.
- [6] J.R. Miller, P. Simon, *Science* 321 (5889) (2008) 651.
- [7] K. Kalyanasundaram, M. Gratzel, *J. Mater. Chem.* 22 (46) (2012) 24190.
- [8] G.M. Shafiullah, et al. *Renew. Sustain. Energy Rev.* 20 (0) (2013) 306.
- [9] R. Singh, A.D. Setiawan, *Renew. Sustain. Energy Rev.* 22 (0) (2013) 332.
- [10] P. Würfel, *Physics of Solar Cells: From Basic Principles to Advanced Concepts*, Wiley-VCH, 2009.
- [11] P. Simon, et al. *Science* 343 (6176) (2014) 1210.
- [12] P. Simon, Y. Gogotsi, *Nat. Mater.* 7 (11) (2008) 845.
- [13] M. Winter, R.J. Brodd, *Chem. Rev.* 104 (10) (2004) 4245.
- [14] M. Armand, J.M. Tarascon, *Nature* 451 (7179) (2008) 652.
- [15] Z. Yang, et al. *Chem. Rev.* 111 (5) (2011) 3577.
- [16] P. Ruetschi, *J. Power Sources* 2 (1) (1977) 3.
- [17] D. Larcher, J.M. Tarascon, *Nat. Chem.* 7 (1) (2015) 19.
- [18] D. Aurbach, et al. *Adv. Mater.* 19 (23) (2007) 4260.
- [19] G.L. Soloveichik, *Annu. Rev. Chem. Biomol.* 2 (1) (2011) 503.
- [20] J.R. Owen, *Chem. Soc. Rev.* 26 (4) (1997) 259.
- [21] N. Nitta, et al. *Mater. Today* 18 (5) (2015) 252.
- [22] J.B. Goodenough, *Acc. Chem. Res.* 46 (5) (2012) 1053.
- [23] N. Yabuuchi, et al. *Chem. Rev.* 114 (23) (2014) 11636.
- [24] M.H. Han, et al. *Energy Environ. Sci.* 8 (1) (2015) 81.
- [25] M.D. Slater, et al. *Adv. Funct. Mater.* 23 (8) (2013) 947.
- [26] P. Saha, et al. *Prog. Mater. Sci.* 66 (0) (2014) 1.
- [27] M.M. Huie, et al. *Coord. Chem. Rev.* 287 (0) (2015) 15.
- [28] Q. Li, N.J. Bjerrum, *J. Power Sources* 110 (1) (2002) 1.
- [29] M.-C. Lin, et al. *Nature* 520 (7547) (2015) 324.
- [30] M.S. Whittingham, *Chem. Rev.* 104 (10) (2004) 4271.
- [31] J.B. Goodenough, K.-S. Park, *J. Am. Chem. Soc.* 135 (4) (2013) 1167.
- [32] R. Masse, et al. *Sci. China Mater* 58 (9) (2015) 715.
- [33] H.D. Yoo, et al. *Mater. Today* 17 (3) (2014) 110.
- [34] A. Yoshino, *Angew. Chem. Int. Ed.* 51 (24) (2012) 5798.
- [35] S.R. Bottone, *Galvanic Batteries, Their Theory, Construction and Use, Comprising Primary, Single and Double Fluid Cells. Secondary and Gas Batteries*, Nabu Press, 2010. [36] H. Wu, Y. Cui, *Nano Today* 7 (5) (2012) 414.

- [37] M.N. Obrovac, V.L. Chevrier, *Chem. Rev* 114 (23) (2014) 11444.
- [38] M. Zhang, et al. *Int. Mater. Rev* 60 (6) (2015) 330.
- [39] S. Goriparti, et al. *J. Power Sources* 257 (0) (2014) 421.
- [40] Y. Wang, G. Cao, *Chem. Mater.* 18 (12) (2006) 2787.
- [41] M. Winter, et al. *Adv. Mater.* 10 (10) (1998) 725.
- [42] A.S. Arico, et al. *Nat. Mater.* 4 (5) (2005) 366.
- [43] M. Noel, V. Suryanarayanan, *J. Power Sources* 111 (2) (2002) 193.
- [44] A.D. Roberts, et al. *Chem. Soc. Rev.* 43 (13) (2014) 4341.
- [45] E. Antolini, *Solid State Ionics* 170 (3–4) (2004) 159.
- [46] J. Wang, X. Sun, *Energy Environ. Sci.* 8 (4) (2015) 1110.
- [47] L.-X. Yuan, et al. *Energy Environ. Sci.* 4 (2) (2011) 269.
- [48] R. Koksang, et al. *Solid State Ionics* 84 (1–2) (1996) 1.
- [49] J.-K. Park, *Principles and Applications of Lithium Secondary Batteries*, Wiley- VCH Germany, 2012.
- [50] M.S. Islam, C.A. Fisher, *J. Chem. Soc. Rev.* 43 (1) (2014) 185.
- [51] D.P. Dubal, et al. *Chem. Soc. Rev.* 44 (1) (2015) 1777.
- [52] H.D. Abruna, Y. Kiya, I.C. Henderson, *Phys. Today* 61 (12) (2008) 43. RESEARCH Materials Today _ Volume 19, Number 2 _ March 2016 FIGURE 14 Schematic of the density of states (DOS) of Li₂RuO₃ and Li₂MnO₃ (top) and Li_{2-x}Ru_{0.5}Mn_{0.5}O₃ (bottom) in which the Fermi level (EF) is represented by a horizontal dotted line. Mn⁴⁺(3d), Ru⁴⁺(4d), and O₂(2p) energy levels indicate the more electronegative character of Ru compared with Mn, and then the stronger Ru(4d)–O(2p) hybridization compared with Mn(3d)–O(2p). The virtual oxidation of Ru⁵⁺ into Ru⁶⁺ is shown in the inset [138]. 122 RESEARCH:
- [53] R. Mukherjee, et al. *Nano Energy* 1 (4) (2012) 518.
- [54] P. Roy, S.K. Srivastava, *J. Mater. Chem. A* 3 (6) (2015) 2454.
- [55] W. Shi, et al. *J. Phys. Chem. C* 116 (51) (2012) 26685.
- [56] J. Wang, X. Sun, *Energy Environ. Sci.* 5 (1) (2012) 5163.
- [57] L. Su, et al. *Nanoscale* 3 (10) (2011) 3967.
- [58] I. Lahiri, W. Choi, *Crit. Rev. Solid State* 38 (2) (2013) 128.
- [59] A.L.M. Reddy, et al. *Adv. Mater.* 24 (37) (2012) 5045.
- [60] N. Brun, et al. *J. Phys. Chem. C* 116 (1) (2012) 1408.
- [61] M. Srivastava, et al. *Nanoscale* 7 (11) (2015) 4820.
- [62] V. Augustyn, et al. *Energy Environ. Sci.* 7 (5) (2014) 1597.
- [63] D. Li, H. Zhou, *Mater. Today* 17 (9) (2014) 451.
- [64] A. Van der Ven, et al. *Acc. Chem. Res.* 46 (5) (2013) 1216.
- [65] F. Bonaccorso, et al. *Science* 347 (2015) 6217.
- [66] M.S. Whittingham, *Chem. Rev.* 114 (23) (2014) 11414.
- [67] E. Uchaker, G. Cao, *Nano Today* 9 (4) (2014) 499.
- [68] L. Mai, et al. *Chem. Rev.* 114 (23) (2014) 11828.
- [69] N. Liu, et al. *Front. Phys.* 9 (3) (2014) 323.
- [70] D. Aurbach, et al. *Nature* 407 (6805) (2000) 724.
- [71] D. Kundu, et al. *Angew. Chem. Int. Ed.* 54 (11) (2015) 3431.