J. Electrochem. Sci. Eng. **13(4)** (2023) 591-604; http://dx.doi.org/10.5599/jese.1544

Open Access : : ISSN 1847-9286
www.jESE-online.org

Review paper

A general introduction to lithium-ion batteries: From the first concept to the top six commercials and beyond

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Received: October 14, 2022; Accepted: January 24, 2023; Published: February 8, 2023

Abstract

The birth of lithium-ion batteries (LIBs) is not a breakthrough scientific discovery overnight but a successor and continuous development of scientists for a long time based on the previous generation of electrochemical batteries. The development of LIBs and succeeding generations of batteries, however, is highly hopeful given the broad commercialization of LIBs during the previous ten years. Intensified research is required to create next-generation LIBs with drastically better performance, including enhanced energy density, charging rate, lifespan, stability, and safety, in order to fulfill the rising demand for energy storage. Research into LIBs and next-generation is currently in an explosive phase with the goal of overcoming the significant challenge posed by conventional LIBs that can keep up with the rapidly evolving needs of the electronics, mechanical, and automation industries, particularly electric vehicles. In this case, this tutorial review might offer a broad overview of LIBs as well as an optimistic look toward the upcoming generation.

Keywords

Energy storage; secondary batteries; cathode; anode; electrochemistry

Introduction

One of the most technologically sophisticated rechargeable batteries on the market, lithium-ion batteries, has attracted a lot of attention and is now the standard mobile power source for portable electronic devices, which are widely used in various fields [1,2]. Electric and hybrid vehicles, which demand next-generation LIBs with not only high power, high capacity, high charging rate, and long life, but also significantly enhanced safety performance and low cost, are another significant expanding market for LIBs [3,4]. Rechargeable batteries are being used more frequently as a result of the rise in portable consumer electronics that run on batteries. Additionally, it is anticipated that over the course of the projection period, demand for lithium-ion batteries will rise due to rising global sales of electric vehicles and the presence of market participants in the nation [5-8]. In order to meet the high performance and power density demands of gadgets, battery technology is constantly developing. In the upcoming years, electric and hybrid electric cars are anticipated to be the major consumers of lithium-ion batteries. Over the forecast period, rising fossil fuel prices and increased public awareness of the advantages offered by battery-powered vehicles are expected to support the growth of the automotive application category [9-10].

Before the advent of lithium-ion batteries, most electronic devices and portable compact devices used the first generation of dry batteries (primary generation). These are the first generations of batteries, such as lead-acid, zinc-carbon and nickel-cadmium (the first alkaline battery) batteries with low capacity, just enough for use in small compact devices [11-14]. For equipment that requires a larger power supply for the purpose of supporting voltage or creating a starting source, such as gasoline cars, generators, and mechanical machine tools, it is preferable to use batteries belonging to the second generation of nickel metal hydride batteries, such as nickel-iron (NiFe), nickel-cadmium (NiCd), and nickel metal hydride batteries (NiMH) [13,14]. The period of the 1980s was the time of the explosion of rechargeable alkaline batteries with their presence in all areas of life, from the TV remote controls to portable music players, even egg beaters in the kitchen [15,16]. However, with low energy density, short lifetime due to leakage of a corrosive liquid that damages the electrodes, flammable when recharging, and high internal resistance that reduces the output devices, they have promoted scientific research and developed new generations of batteries. In the 1990s, the appearance of the first type of lithium battery (1913 by Gilbert N. Lewis), which led to the commercialization of LIBs in the 1970s, forever changed the game [17-22].

Currently, LIBs have appeared in a variety of fields, particularly consumer electronics, especially portable devices such as remote controls, cell phones, laptop computers, digital cameras, portable healthcare devices, mechanical power tools, *etc.* [23,24]. Also included are electric vehicles (electric cars, motorcycles, scooters, bicycles, and advanced wheelchairs) and stationary energy storage [25,26]. It is not an exaggeration to say that our lives today would be impossible to imagine without the use of batteries. Furthermore, LIBs are seen as an alternative to gasoline and energy supply solutions, particularly in the current automotive industry revolution [27]. Electric cars powered by LIBs have emerged as a development trend for the 2030s [28-30].

The goal of this review is to present a comprehensive picture of the introduction of lithium-ion technologies and several distinct types of LIBs. In addition, the discussion covers new developments and technological problems relating to the next-generation secondary battery systems. Also included is statistical data about the present and upcoming industry demand.

The adventure of lithium-ion batteries from the first concept to the 6 top commercial types

The majority of portable compact electronics and electronic devices used the first generation (primary generation) of dry batteries prior to the development of lithium-ion batteries. These are the initial iterations of low-capacity batteries, such as lead-acid, zinc-carbon, and nickel-cadmium (NiCd) batteries. Batteries from the second generation of rechargeable alkaline batteries, including nickel-iron (NiFe), nickel-cadmium (NiCd), and nickel metal hydride (NiMH), are recommended for equipment that needs a larger power supply to support voltage or create a starting source, such as gasoline cars, generators, and mechanical machine tools [31,32]. Rechargeable alkaline batteries became extremely popular in the 1980s and have been found everywhere until today [33]. However, the safety, hazard, and recycling problems of rechargeable alkaline batteries require the development of the next generation to overcome the previous barrier.

The adventure of lithium-ion batteries began in 1965 when NASA tried to create a new generation of batteries using CuF_2/Lithium electrodes [34]. According to the flow of time (Figure 1), in the 1970s, M. Stanley Whittingham introduced TiS_2 material as an electrode that showed high performance, but its high cost and toxic emissions of H_2S were a great barrier to commercialization [35,36]. Then came the period of the 1980s–1990s, which was a golden time in the development history of lithium-ion batteries with announcements that changed the history of energy storage components; new electrode materials such as $LiCoO_2$ and graphite leading to the first commercialization of lithium-ion batteries for portable electronic devices [37-38]. Until the 2000s, lithium-ion batteries were developed and commercialized massively with many different types, such as $LiMnCoO_2$, $LiMnO_2$, $LiFePO_4$, *etc*. Thus, three scientists Michael Stanley Whittingham, John Bannister Goodenough, and Akira Yoshino were awarded the Nobel Prize in Chemistry in 2019 for their pioneering contributions to lithium-ion battery research.

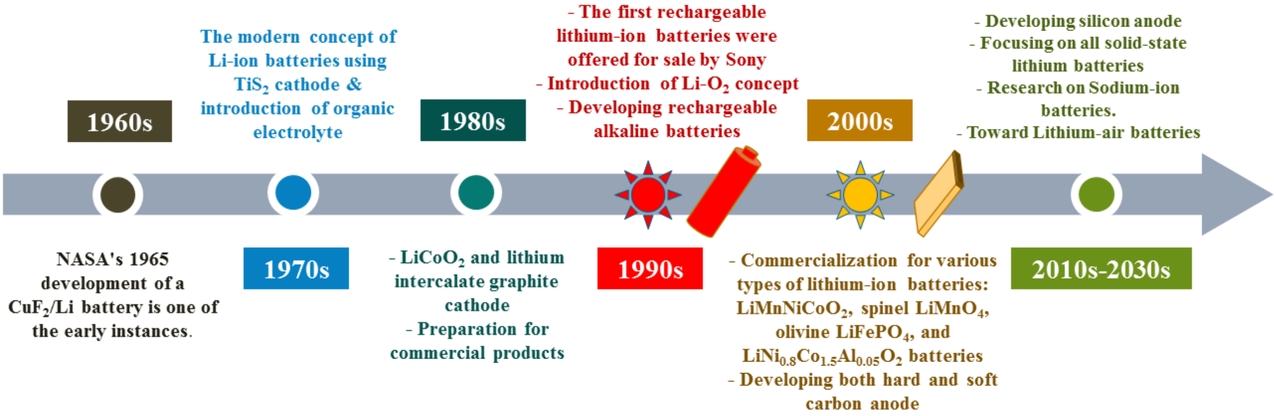

Figure 1. *A general developing timeline of lithium-ion batteries from the 1960s to the 2030s*

Lithium-ion batteries are classified in the industry based on their cathode chemical composition. Currently, some most popular commercial lithium-ion batteries can be listed, such as lithium cobalt oxide (LCO), lithium nickel oxide (LNO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), lithium nickel cobalt aluminum oxide (NCA), lithium titanate (LTO) [39-43].

Lithium-ion battery definition and operation principle

The first battery was invented in 1800 by an Italian physicist named Alessandro Volta. In an electrochemical reaction, electrons are moved from one material (referred to as an electrode) to another through an electric current. In general, a battery is a chemical device that turns chemical energy into direct current (DC) electric energy through an electrochemical reaction after storing electrical energy in the form of chemicals. Throughout the 19th century, the first-generation battery was the only choice and held the dominant position. Typical batteries for this era of dominance include lead acid, zinc-carbon, alkaline, nickel-cadmium, and the first generation of nickel metal hydride rechargeable batteries [44-46].

In fact, there has been more than five decades since people used first-generation batteries such as lead-acid, zinc-carbon, and alkaline batteries. However, with the rapid development of electronic, semiconductor, mechanical, and especially information technologies in the early 20th century, the old battery generations seemed overloaded with more advanced applications that required durability and convenience. Cost-effective batteries such as zinc-carbon and nickel oxyhydroxide batteries are non-rechargeable and short-life, while lead-acid batteries are toxic, and alkaline batteries are unstable and leak electrolyte easily after a period of use, also known as the phenomenon of potassium compound leakage [47,48]. The first generation of rechargeable batteries, the nickel–cadmium battery, had a negative impact on the environment when using cadmium chemicals, which is a toxic heavy metal. The most stable battery in terms of price and performance in this first generation is the nickel-metal hydride batteries, which is rechargeable and offers high energy density. However, nickel-metal hydride batteries also have some major problems, such as self-discharge, memory effect, and relativity short cycle [48-50]. Due to their low cost and simple production procedure, several types of batteries, such as lead-acid, zinc-carbon, and alkaline, have been utilized for basic and simple activities in portable electronic devices such as remote controls, children's toys, etc. However, recycling these batteries is a major undertaking. Because of these factors, as well as the rapid advancement of science and technology toward the end of the nineteenth and beginning of the twentieth centuries, a new generation of batteries with high energy density, rechargeable, long lifespan, and high-temperature operation was required. That is why lithium batteries have stepped out of the stage curtain and changed the game.

One typical lithium-ion battery cell is made by five main components: an anode, a cathode, a separator, an electrolyte, and two current collectors (positive and negative) (Figure **2**). The anode and cathode store lithium, while the separator creates a separate layer between the two electrodes, and the migration of lithium ions from the anode to the cathode depends on whether the battery is charging or discharging. Herein, the mobility of the lithium ions in the anode generates free electrons, resulting in a charge on the positive current collector. After that, the electrical current passes from the current collector to the negative current collector through a powered device. The separator keeps electrons from flowing within the battery.

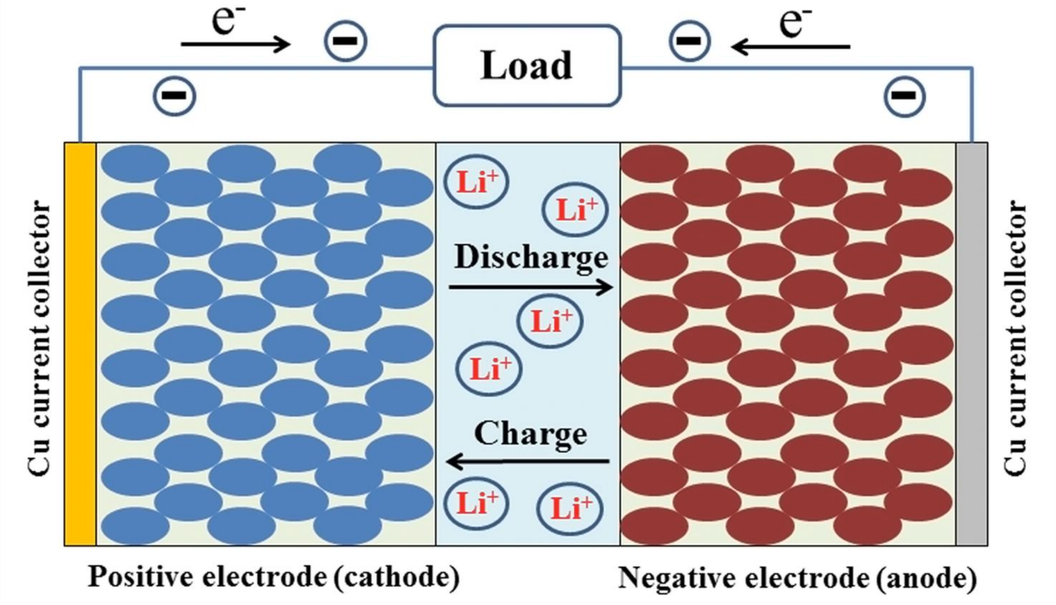

Figure 2. *The working principle of one lithium-ion battery cell is depicted schematically*

Rechargeable lithium-ion batteries operate on the basis of lithium's small atomic radius, light atomic weight, and low reductive potential, which give Li batteries an advantage in terms of high energy density. Electrode materials may be classified into three main categories based on the way that lithium reacts with them: conversion, intercalation, and others (Figure 3) [51-55]. The charge/discharge process in conversion intercalation electrodes, such as LMO, LCO typically involves a conversion reaction and is always accompanied by phase transitions, which increases the specific capacity but also leads additional unstability issues like structural collapse due to lithium dendrites, increasing temperature, growth of solid electrolyte interface (SEI) on the anode, formation of electrolyte oxidation (EO) at the cathode leading poor reversibility. In contrast, intercalation electrode materials are frequently used in commercialized cells due to increase in durability. In the intercalation electrode, Li ions intercalate and deintercalate reversibly, producing steady cycling but a decreased specific capacity (Figure 3b) [54,55].

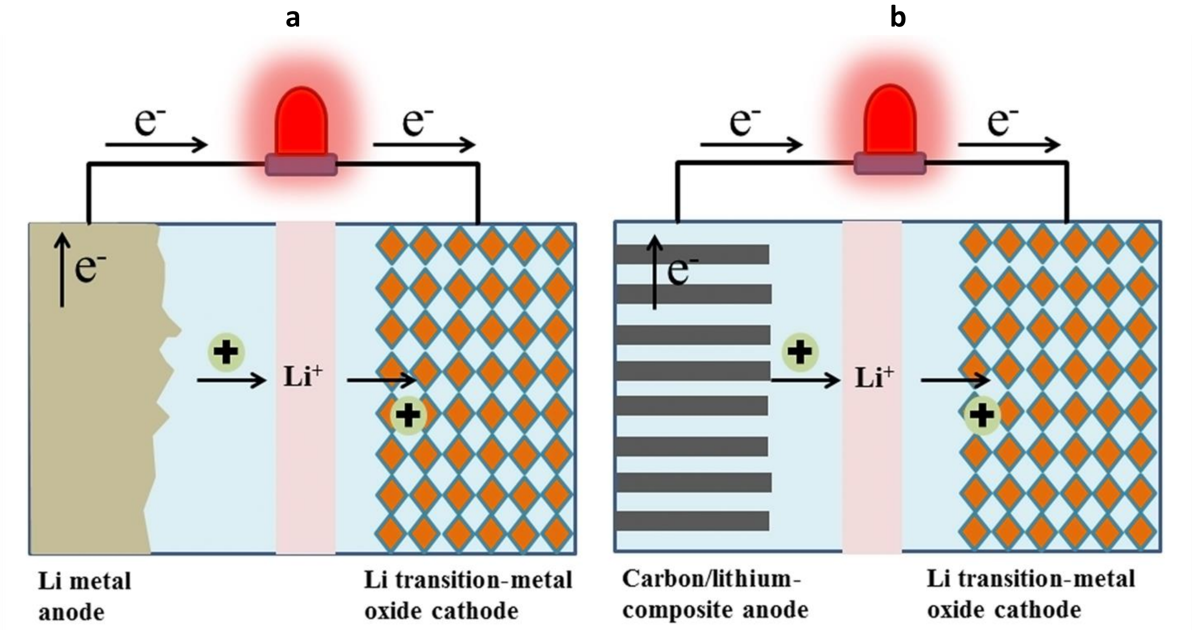

Figure 3. *General working principle of battery for (a) battery based on the conversion reaction, and (b) battery based on the intercalation reaction*

Different chemistries of lithium-ion batteries

The names of the various lithium battery types are derived from their active materials. The chemistry, cost, size, weight, capacity, and many other characteristics differ between different types of lithium ion batteries. Until now, six commercial types have been widely used in a variety of fields, particularly electronic technology and electric vehicles, as well as electricity storage for solar cells and wind power.

Lithium cobalt oxide ($LiCoO_2$) - LCO

Cobalt oxide cathode with a layered structure and a graphite anode make up lithium cobalt oxide batteries, commonly known as lithium-ion cobalt batteries. Lithium ions migrate in two directions: during the discharge process, the lithium ions move from graphite to layer cathode and during the charge process, the lithium ions move from layer cathode to graphite anode. But because of changes in the solid electrolyte interface and anode thickness, the graphite electrode also reduces battery life (Table 1) [39,41,56].

Table 1. *LCO type characterizations, $LiCoO_2$ cathode and graphite anode*

Commercial time	1991
Voltage, V	3.6 - with working voltage window of 3.0 to 4.2 V per cell
Energy density, Wh kg^{-1}	150 – 200 typical
Charge (C-rate)	0.7–1 C. Charge current above 1 C shortens battery life.
Discharge (C-rate)	1 C. Discharge current above 1 C shortens battery life.
Cycle life, cycles	500 - 1000
Thermal runaway, °C	150
Applications	Consumer electronics (cell phones, laptops, tablets, *etc.*)

The LCO type has a short life expectancy, poor thermal stability, and constrained load capabilities. The graphite anode of the LCO type herein limits the cycle life due to a changing solid electrolyte interface (SEI), anode thickening, and lithium plating [56].

Lithium manganese oxide ($LiMn_2O_4$) - LMO

Lithium manganese oxide, also known as lithium manganate, is a spinel-structured cathode material that can be discharged at high rates. This structure produces a three-dimensional structure that enhances thermal stability and safety while enhancing ion flow, decreasing internal resistance, and increasing current handling [57]. Although lithium manganese oxide batteries have a lower cycle and lifespan than other lithium-ion battery types, they are known for their great temperature stability (Table 2) [58].

Table 2. *LMO type characterizations, $LiMn_2O_4$ cathode and graphite anode*

Commercial time	1996
Voltage, V	3.7 - with working voltage window of 3.0 - 4.2 V per cell
Energy density, Wh kg^{-1}	100 – 150 typical
Charge (C-rate)	0.7–1 C with maximum until 3 C, and charges to 4.2 V
Discharge (C-rate)	1 C with maximum until 10 C for special versions
Cycle life, cycles	300–700
Thermal runaway, °C	250
Applications	Power tools, medical devices, some kind of electric vehicles

Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$) - NMC

The most popular variety of LIBs, the NMC battery type, combines the benefits of nickel, manganese, and cobalt cathode. Nickel and manganese together form the basis of this specific sort of lithium-ion battery. While manganese has low internal resistance but high specific energy, nickel is noted for having high specific energy but poor stability. The right combination of both metals in a cell can produce the necessary balance of both metals' qualities (Table 3) [42,59].

Nickel, manganese, and cobalt are frequently combined in equal amounts to form the cathode combination, or 1-1-1. By lowering the cobalt concentration, this combination keeps some important performance criteria while lowering costs. Although NMC battery types offer a long lifespan and good energy options, they are also quite expensive and less safe than other lithium-ion battery types [59].

Table 3. *NMC type characterizations, $LiNiMnCoO_2$ cathode and graphite anode*

Commercial time	2008
Voltage, V	3.6 and 3.7 - with working voltage window of 3.0 - 4.2 V per cell
Energy density, Wh kg^{-1}	150–220
Charge (C-rate)	Only from 0.7 to 1 C
Discharge (C-rate)	1C
Cycle life, cycles	1000–2000
Thermal runaway, °C	210
Applications	Power tools, medical devices and electric vehicles

Lithium Iron phosphate ($LiFePO_4$) - LPO

Lithium iron phosphate batteries, based on nanoscale phosphate cathode material, have excellent electrochemical performance with low resistance [60]. The highest current rating, prolonged cycle life, better thermal stability, increased safety, and higher abuse tolerance are the most significant benefits (Table 4) [39,41,60].

When considering their lengthy battery lives, the LPO type is frequently the most affordable choice. On the other hand, compared to other lithium battery types, the LPO has a lower voltage and, therefore, less energy.

Table 4. *LPO-type characterizations, $LiFePO_4$ cathode and graphite anode*

Commercial time	1996
Voltage, V	3.2 - with working voltage window of 2.5 - 3.65 V per cell
Energy density, Wh kg^{-1}	90–120
Charge (C-rate)	1 C
Discharge (C-rate)	1 C
Cycle life, cycles	~2000
Thermal runaway, °C	270
Applications	Power tools

Lithium nickel cobalt aluminum oxide ($LiNiCoAlO_2$) - NCA

Lithium nickel cobalt aluminum oxide is a cathode material used in lithium-ion batteries that provide highly thermally stable, long lifecycle, good specific power, and high specific energy device (Table 5) [42,61]. Aluminum doping stabilizes the thermal and charge transfer resistance of lithium-nickel cobalt oxide. Due to research for the car industry, this kind is rarely used in consumer applications. The NCA battery type has a high cost and low safety compared to other lithium-ion battery types, despite its high capability and endurance [61].

Table 5. *NCA type characterizations, $LiNiCoAlO_2$ cathode and graphite anode*

Commercial time	1999
Voltage, V	3.6 - with working voltage window of 3.0 - 4.2 V per cell
Energy density, Wh kg^{-1}	200-260
Charge (C-rate)	~0.7 C
Discharge (C-rate)	1 C typical
Cycle life, cycles	500
Thermal runaway, °C	150
Applications	Automotive industry

Lithium titanate (Li_2O–TiO_2 composition line) - LTO

The rechargeable battery type known as lithium titanate or lithium-titanium-oxide batteries has the benefit of a quicker charging time than other types but the limitation of having a significantly lower energy density (Table 6) [39,51,62].

Table 6. *LTO type characterizations, LMC or NMC cathode and Li_2TiO_3 anode*

Commercial time	2008
Voltage, V	2.4 - with working voltage window of 1.8 - 2.85 V per cell
Energy density, Wh kg^{-1}	50–80
Charge (C-rate)	1 C typical with maximum until 5 C
Discharge (C-rate)	From 1 C to maximum 10 C
Cycle life, cycles	3000–7000
Thermal runaway, °C	100
Applications	Automotive industry, electric power train

In this type of battery, lithium-titanium oxide replaces graphite in the anode and forms a spinel structure, whereas the cathode might be lithium manganese oxide (LMO) or lithium nickel manganese cobalt oxide (NMC) [62].

Introduction of lithium-ion batteries commercial form

Lithium-ion batteries are available in a range of forms, including cylindrical cell, prismatic cell, and pouch cell, depending on the intended use and device design (Figure 4). Although there are obviously distinct forms for various applications, the same essential concepts are employed.

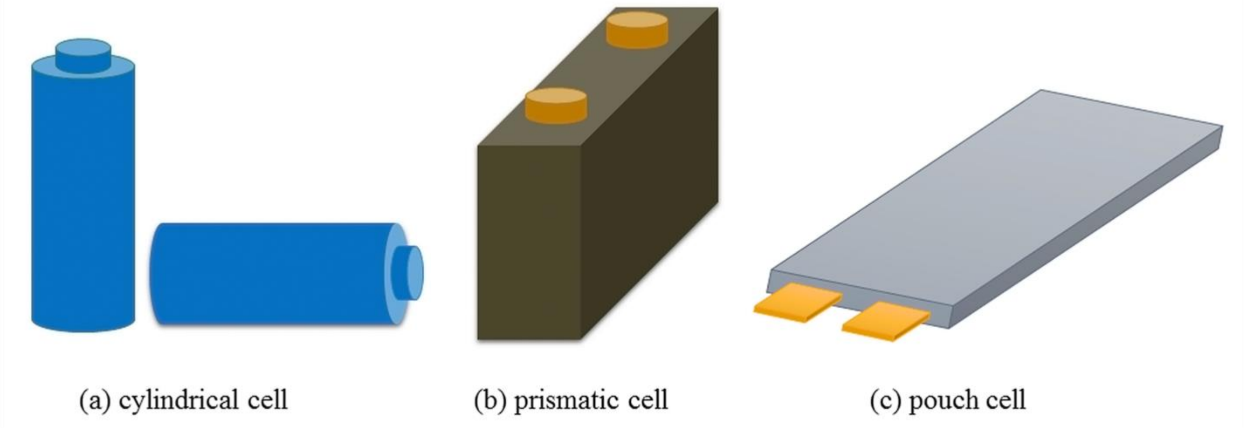

Figure 4. *Three main types of lithium-ion batteries: (a) cylindrical cells, (b) prismatic cells, and (**c**) pouch cells*

Lithium cylindrical cell batteries

A lithium cylindrical battery is a cell packed and rolled with thin flat electrodes inside a rigid cylinder. Batteries are commonly made from a sequence of these cylindrical cells since they are widely employed in a range of applications. The three standard sizes are currently 18×65 mm, 21×50 mm, and 26×65 mm. Because they are compact and spherical, lithium cylindrical cells have the benefit of being stackable in a variety of devices. Additionally, this type may cost-effectively employ the preceding battery's manufacturing method. The drawbacks of this form are that it is heavy and underpowered (Table 7) [63].

Lithium prismatic cell batteries

Introduced in the early 1990s, lithium prismatic cell batteries have a higher power density than cylindrical cell batteries. They are generally flat or rectangular in shape and are frequently employed to power electronic devices and automobiles. They also provide superior performance in colder climates and are less vulnerable to vibration damage, so they are an excellent choice for building large battery packs for energy storage [64]. However, they have the disadvantage of being more expensive to manufacture than cylindrical cells. Currently, lithium prismatic cell batteries are predominantly used in cell phones, laptops, portable medical tools, and other portable electronic devices (Table 7) [63,64].

Lithium pouch cell batteries

Lithium pouch cells were first commercialized in 1995, with the construction of conductive foil tabs welded to the electrode and sealed to the pouch to convey the positive and negative terminals to the outside. Because it has the maximum capacity among battery packs, the pouch cell makes the most effective use of space. Lithium-ion pouch cell batteries are popular due to their lightweight, simple, and flexible architecture. However, this format uses a polymer bag cover, which is less durable and mechanically strong in comparison with a cylindrical cell using a metal cover.

Furthermore, the gas is released by the expansion or swelling of pouch cells over a long period of charge-discharge, resulting in a shorter lifespan and making it easily flammable. Temperature and humidity are also big factors that have an effect strongly on pouch cells. Despite some disadvantages, lithium pouch cell batteries are one of the most popular formats and are available in a variety of sizes and thicknesses depending on the applications (Table 7) [62,65].

Table 7. *Comparison of three main lithium-ion batteries format*

Type	Main advantages	Main disadvantages
Cylindrical cell	• Low-cost due to using the preceding battery's manufacturing method. • Mechanical stability due to cylindrical shape with metal protected cover. • Large scale systems using many small cells will easily dissipate heat because of the space between the cylindrical cells.	• Cylindrical cells have a low packing density due to the round cross-section of the cell, preventing full use of the available space. • Increase the weight and complexity of large scale cell (using a large number of small cells).
Prismatic cell	• Optimal utilization of battery packs and easily increases the size. • Not swelling after long time working. • Higher energy density in comparison with the other types.	• Expensive to manufacture. • The interior electrodes are easily prone to expansion and contraction, which might result in deformation and an internal short circuit.
Pouch cell	• Lowest weight with lowest thickness • Easily fitting with the limitation available space in a product.	• Poor heat dissipation ability is easily affected by high temperatures. • Decreasing lifespan due to gas release during long cycle charge-discharge.

The current lithium-ion battery technology almost achieves maximum energy density. The great variety of cell designs and chemistries available allows for fine-tuning of characteristics like rapid charge-discharge and a wide temperature working window. Additionally, lithium-ion batteries exhibit benefits, including very low self-discharge, an extremely long lifespan, and cycling capabilities that can generally withstand thousands of charging and discharging cycles. Lithium-ion battery technology is anticipated to hit an energy limit during the next few years using existing materials and cell designs. However, relatively recent research into novel materials should be able to overcome current constraints, which can store more lithium in positive and negative electrodes. Additionally, the rarity and importance of raw materials are taken into consideration with these novel compounds.

Future beyond lithium-ion batteries

Although Li-ion battery technology has been around for 50 years, it is regrettably getting close to its theoretical limitations and isn't keeping up with advances in electronic technology, which call for longer lifespans, higher energy densities, and lower prices. Although the search for a better battery has always been continuous, there is now a sense of urgency since battery shortages are stifling not only consumer devices but also the clean energy sector's efforts to develop electric vehicles and associated technologies. Some of the next battery generations are considered to aim at alternative lithium-ion batteries in the near future, such as lithium-sulfur batteries, sodium-ion batteries, metal-air batteries, and solid-state batteries.

Lithium-sulfur batteries

Lithium-sulfur batteries are rechargeable types like lithium-ion batteries in which there are no host structures inside: the lithium anode is consumed during the discharge process, and sulfur is converted into a variety of chemical compounds; this process is reversed while charging. Due to the use of sulfur in the positive electrode, lithium-sulfur batteries have the benefit of being lighter and having a plentiful precursor. Following the theoretical simulation, the lithium-sulfur batteries have nearly four times greater energy density than lithium-ion batteries. However, lithium-sulfur batteries face some major limitations of high cost and decreasing lifetime due to the charging process in one lithium-sulfur cell making a chemical deposition on the electrodes [66]. Currently, various kinds of solid-state electrolytes have been studied for combination in lithium-sulfur batteries in order to overcome this chemical deposition problem.

Sodium-ion batteries

Sodium-ion batteries are also one type of rechargeable battery as lithium-ion batteries where replacing lithium electrode and Li^+ ions with sodium electrodes and Na^+ ions electrolyte as the charge carriers. Sodium-ion batteries have much attraction due to large natural sodium resources, which decrease the price and lower the average cost per kilowatt hour of capacity. The idea of using hard carbon anode and sodium cathode brings the advantages of cost-effectiveness, leading to scaled production. However, sodium-ion batteries need to improve some properties, such as energy density, short cycle life and incomplete industrial chain [67].

Metal-air batteries

Like lithium-ion batteries, metal-air batteries are secondary generation cells. The positive electrode (external cathode of ambient air) in metal-air batteries is made of carbon and covered with various precious metals to react with oxygen. Metal anodes (the negative electrode) are constructed using a variety of metals, including zinc, aluminum, magnesium, and lithium. Theoretically having a substantially higher energy density than lithium-ion batteries, metal-air batteries are commonly promoted as a next-generation electrochemical energy storage option for grid energy storage or electric vehicle applications [68]. However, because of difficulties with the metal anode, air cathode, and also aqueous electrolyte, they have not reached their full potential. Before metal-air batteries can be used on a large scale and become a practical reality, these issues must be appropriately addressed.

Solid-state batteries

Solid-state batteries are interesting novel energy storage devices using solid electrolytes instead of aqueous and gel polymer electrolytes, which avoid electrolyte leak and explosion [69]. Therefore, there is no need for safety-related components, which frees up more space. Currently, solid-state batteries have been focused strongly and firstly commercialized for electric vehicles as testing products. With higher energy density and larger cells in the same space as lithium-ion batteries, solid-state batteries may take a piece of the global market in the near future. The solid battery is in intensive research and very small-scale testing for the purpose of being widely developed in the future. Currently, solid batteries still have some major problems that need to be solved, such as high production costs, high resistance in the contact area between the electrode and the electrolyte, and the phenomenon of dendrite in the type of lithium solid-state battery [70].

Conclusions

In summary, this review provided an overview of the development of lithium-ion batteries from the first concept to the six most popular types, with their advantages and limitations. Additionally, the development of next-generation lithium-ion batteries is also covered, with a favorable outlook on their future in the domains of rigid energy storage and electric vehicles.

Nowadays, batteries have always been a crucial component of various designs, but notably in electrical technologies and grids for energy storage. Research has been ongoing for years in order to boost the energy density and longevity of batteries following the rise in portable electronic equipment, from handheld gadgets to industrial measuring instruments, which has created a need for higher energy densities. Battery capacities frequently take center stage in technological advancements while researchers have been attempting to improve battery technology. However, electronic technology continues to grow more rapidly and needs more energy and power than ever before.

As the electronic industry has grown, lithium-ion batteries have developed ever-higher energy densities. The operational time of a battery is proportional to its energy density. To reach better densities, battery industry experts have constantly modified the chemistries and designs of the technology. Currently, there are various types of novel materials have been studied as the new electrode and new electrolyte aiming to not only reduce the cost but also increase the energy density and expand the lifespan.

Acknowledgements: *This work belongs to series of research on batteries and recycling technology that has been led by Dr. Phuoc-Anh Le. The authors wish to acknowledge the support given by the Vietnam-Japan University, Vietnam and Shinshu University, Japan.*

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