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REVIEW ARTICLE

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A review of rechargeable batteries for portable electronic devices

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Abstract

Portable electronic devices (PEDs) are promising information-exchange platforms for real-time responses. Their performance is becoming more and more sensitive to energy consumption. Rechargeable batteries are the primary energy source of PEDs and hold the key to guarantee their desired performance stability. With the remarkable progress in battery technologies, multifunctional PEDs have constantly been emerging to meet the requests of our daily life conveniently. The ongoing surge in demand for high-performance PEDs inspires the relentless pursuit of even more powerful rechargeable battery systems in turn. In this review, we present how battery technologies contribute to the fast rise of PEDs in the last decades. First, a comprehensive overview of historical advances in PEDs is outlined. Next, four types of representative rechargeable batteries and their impacts on the practical development of PEDs are described comprehensively. The development trends toward a new generation of batteries and the future research focuses are also presented.

KEYWORDS
electrochemical energy storage, information material, portable electronic device, rechargeable battery

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1 | INTRODUCTION

Nowadays, the information-rich world is becoming more and more portable. With the huge demands for the timely and efficient delivery of global information, information collection and transmission require a portable information-exchange platform for real-time response. Portable electronic devices (PEDs) including mobile phones, portable computers, tablets, and wearable electronic devices are the most promising candidates and have promoted the rapid growth of information processing and sharing.

With the development and innovation of electronic technology, PEDs have been rapidly growing over the past decades. The primary motivation behind this activity is that PEDs are widely used in our daily life from personal devices to high-technology devices applied in aerospace due to the ability to integrate and interact with a human, which have brought great convenience and epoch-making changes, even becoming an indispensable part for almost every person.

In general, stable operated energy sources are mandatory in these devices to guarantee the desired performances.[1] Besides, it is highly required to develop energy storage sources with high safety due to the portability of PEDs. With the growing demands of long runtime of PEDs, the capability of energy storage systems should be upgraded. Accordingly, exploring efficient, long-life, safe, and large-capacity energy storage devices is strongly requested to meet the current challenges of PEDs.

Electrochemical energy storage systems, especially rechargeable batteries, have been widely employed as the energy sources of PEDs for decades and promoted the thriving growth of PEDs.[2,3] To satisfy the continually high requirements of PEDs, significant improvements in electrochemical performances of rechargeable batteries have been attained.[4–6] The rechargeable batteries of PEDs have gone through the lead-acid, nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), lithium-ion (Li-ion) batteries, and so on (Figure 1). Their specific energy and specific power are substantially improved as time goes on.

However, the current battery technology cannot fully catch up with the rapid growth of PEDs.[7] The state-of-the-art technology of rechargeable batteries for PEDs has exposed many drawbacks, that is, limited energy storage capacity, short cycle life, and high self-discharge, which have become constrained bottleneck for the further development of PEDs.[8–10] For instance, the high-power consumption of multifunctional PEDs requires energy storage systems with higher energy, smaller volume, lighter weight, and longer operational time. However, it is challenging for current batteries to satisfy the ever-increasing demands of emerging electrical and electronic equipment. Therefore, the rational design and production of novel batteries has been a relentless-pursued goal for the future PEDs.

Tremendous efforts have been dedicated to improving the electrochemical performances of batteries. Significant progress has been made according to recent literatures.[11–16] There are also numerous excellent reviews that cover the progress of battery technologies.[17–31] Nonetheless, few reviews are focusing on the overview of rechargeable batteries designed for PEDs. Considering the critical contribution of battery technologies to the development of PEDs, it is of great interest to summarize the progress of rechargeable batteries for PEDs in the past decades.

In this contribution, we aim to present and highlight how battery technologies contribute to the fast rise of PEDs. We start with a comprehensive overview of historical advances in PEDs. Four types of representative rechargeable batteries and their practical impacts on the development of different types of PEDs are described in detail. Particular attention is given to those traditional PEDs, such as mobile phones, laptops, digital camera, as well as the newly emerging PEDs, including wearable electronic devices and consumer drones. Finally, the current development trends of the battery technologies and the future opportunities are also presented.

2 | PORTABLE ELECTRONIC DEVICES

PED products have experienced dramatic growth and upgraded at an incredible speed ever since their birth (Figure 2). In particular, the sales of so-called 3C products, that is, computer,

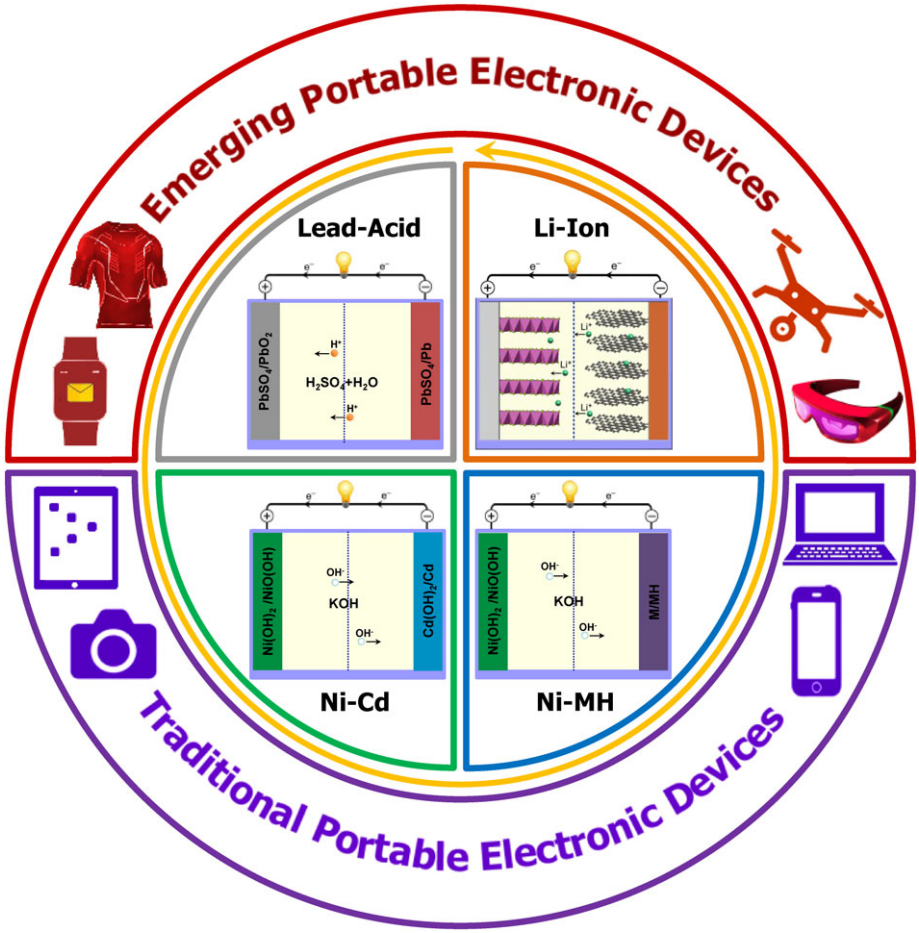

FIGURE 1 Schematic illustration of representative rechargeable batteries and their applications in traditional and emerging portable electronic devices

communication, and consumer electronics are increasing each year rapidly. For example, the mobile phone industry is currently the largest consumer electronics segment in the world. The global shipment of mobile phones increased from 9.6 million in 2003 to 1536 million in 2017 (Figure 3A). The rapid growth of PED products can be ascribed to the following two reasons. First, the increasing demands by customers for information acquisition and information processing

FIGURE 2 Development of various types of portable electronic devices from 1983 until today illustrated by several representative products

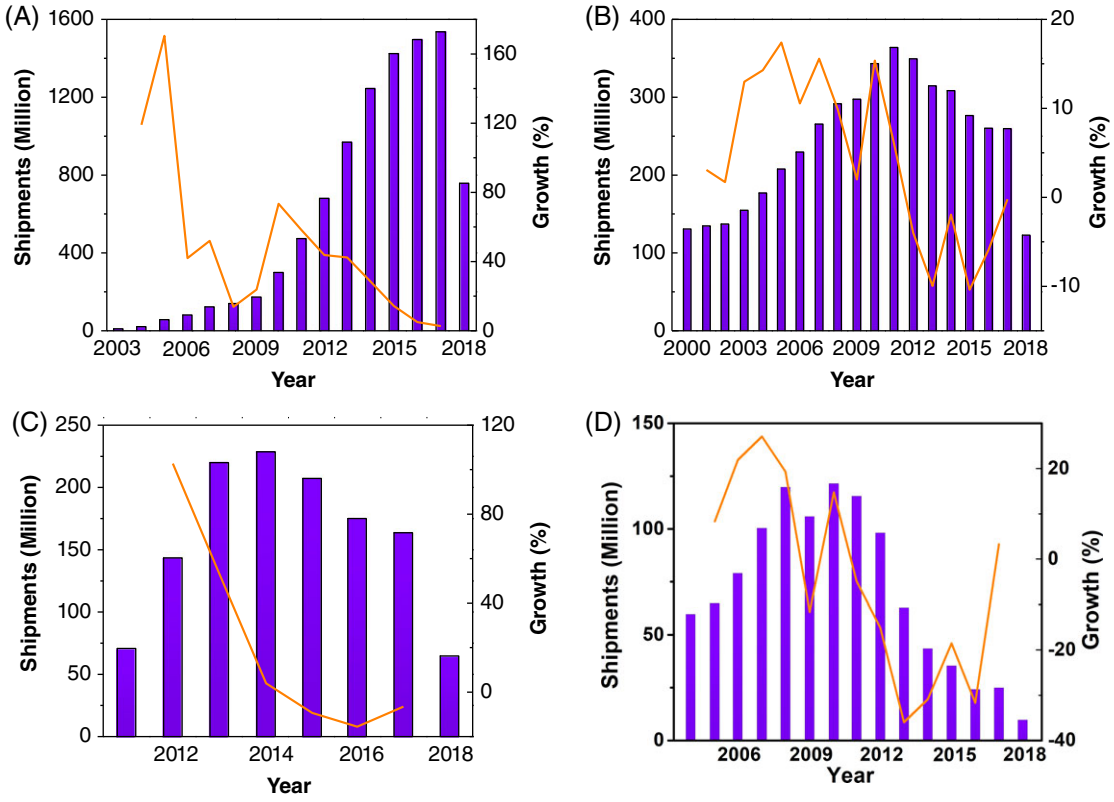

FIGURE 3 Global shipments (violet) and growth rates (orange) of A, mobile phones, B, laptops, C, tablets, and D, digital cameras. Note that data of global shipments in 2018 are taken from Jan to Jun 2018. Data of mobile phones, laptops, tablets, and digital cameras are taken from Gartner, IDC, Wind, and Wind, respectively

capabilities create a fast-growing market for PED products. Second, the continuously reinventing of new PED products is driven by rapid technological progress. For instance, the mobile phones have been updated every 2 years on average since the birth of Big Brother (ie, the first cellular phone) in 1993, where technological progress of semiconductors and other electronic components have played a vital role. Meanwhile, this fast growth is also closely related to the introduction of new battery technologies. Since the birth of the first commercial Li-ion batteries in 1991, PED products based on Li-ion batteries have been springing up, ranging from mobile phones, laptops, digital cameras, Walkman, MP3 players, and tablets, to wearable electronic devices that have become very popular in recent years.

Newly launched PED products usually can open new markets with fast growth rates. With the full saturation of market penetration, their growth would gradually slow down. For example, the market of the traditional PED products, that is, laptops, mobile phones, and tablets has reached certain penetration levels and gradually becomes saturated, resulting in slower growth momentum in recent years. Even though the global shipments of mobile phones increased from 680 million in 2012 to 1536 million in 2017 and the growth rate has dropped from 43.8% to 2.7% (Figure 3A). The laptop market exhibited a negative growth trend since 2012, and had significant decline of 10.4% in 2015, mainly due to the prolonged use cycle of laptops (Figure 3B). Similar negative growth phenomenon can be found in the market of tablets and digital cameras (Figure 3C,D). The global shipments of tablets have fallen since 2015 and decreased 15.5% year-on-year in 2016 to 175 million units. However, due to their large outputs and extensive market penetration, the overall number of traditional PEDs maintains a stable growth rate.

Compared with the traditional PEDs, the emerging new PEDs, including wearable electronic devices, consumer drones, wireless Bluetooth speakers, and other new products, have become an important growth point in the PED industry. For instance, the global markets of wearable electronic devices are growing dramatically, particularly driven by the popularity of sports health tracking devices and smart watches. The global shipment of wearable equipment exceeded 78.1 million in 2015, resulting in an increase of 171.6% compared to 2014. It is estimated that the global shipments of wearable equipment would reach 214 million with an annual growth rate of 20.3% by 2020.[32] The market of consumer drones is another new growth point. The shipment of consumer drones showed a rapid growth trend from 2013 to 2015. It is estimated that the

global shipment of consumer drones would reach 3.1 million units by 2018.

3 | RECHARGEABLE BATTERY TECHNOLOGIES FOR PEDS

The rapid progress of PEDs is impossible without the progressive improvement of rechargeable battery technologies.[33] Primary batteries have already been used as the main energy source of PEDs for a lengthy period. However, the significant strides of rechargeable batteries with higher energy and power density have remarkably changed the situation since the early 21st century. Presently, rechargeable batteries have already been applied in most PEDs.[34]

PEDs evolved and incorporated several different types of rechargeable batteries, including lead-acid, Ni-Cd, Ni-MH, and Li-ion batteries. These rechargeable batteries often adopt four types of shape, that is, coin, cylindrical, prismatic, and pouch cells (Figure 4). Lead-acid and Ni-Cd batteries have been used for a long time. The former can be dated back to 1859, while the latter was first manufactured in 1909. Ni-MH and Li-ion batteries are relatively young. Ni-MH and Li-ion batteries have played critical roles in realizing the widely adaption of PEDs, especially Li-ion batteries. The key characteristics of these four types of batteries are compared in Table 1 and Figure 5. Each type of these batteries and their practical impacts on the development of PEDs will be described and discussed in the following sections.

3.1 | Lead-acid battery

As the first commercially successful rechargeable battery, the lead-acid battery was invented by French physicist Gaston Planté in 1859. Despite its oldest age, the lead-acid battery is continuously used widely today because of its low cost, low self-discharge rate, high discharge currents, and good low-temperature tolerance. These features make them attractive for applications not only in some PEDs but also in automobiles, golf cars, forklifts, and other vehicles.

In a standard lead-acid battery, Pb, PbO_2, and concentrated H_2SO_4 aqueous solution are used as the anode, cathode, and electrolyte, respectively (Figure 6A). The reversible electrochemistry reactions in a lead-acid battery are shown as follows:

$$\text{Cathode}: \quad PbO_2 + 3H^+ + HSO_4^- + 2e^- \rightleftharpoons 2H_2O + PbSO_4$$

$$\text{Anode}: \quad Pb + HSO_4^- \rightleftharpoons PbSO_4 + H^+ + 2e^-$$

$$\text{Overall reaction}: \quad Pb + PbO_2 + 2H_2SO_4 \rightleftharpoons 2PbSO_4 + 2H_2O$$

It is found that in the fully discharged state, both the anode and cathode become $PbSO_4$. The electrolyte loses much of its dissolved H_2SO_4 and becomes water primarily. While in the fully charged state, the cathode and anode

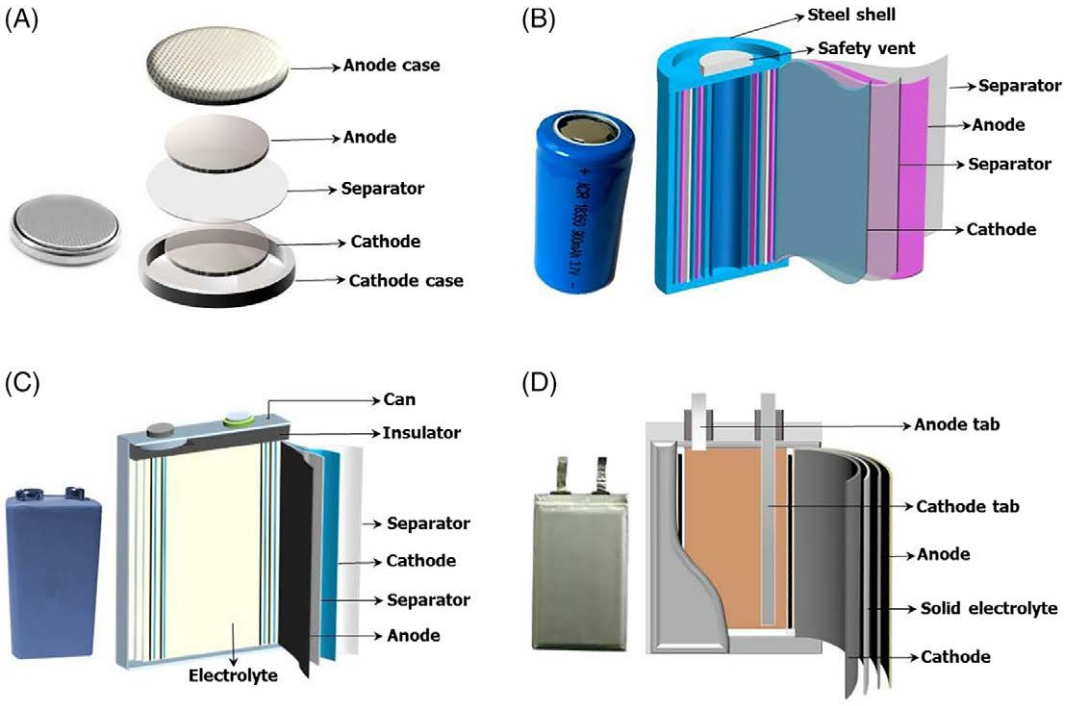

FIGURE 4 Schematic illustration of typical rechargeable battery configurations: A, coin, B, cylindrical, C, prismatic, and D, pouch shapes

TABLE 1 Characteristics of four key types of rechargeable batteries used in PEDs

Characteristics	Lead-acid battery	Ni-Cd battery	Ni-MH battery	Li-ion battery
Gravimetric energy density (Wh kg^{-1})	30-50	40-60	60-120	170-250
Volumetric energy density (Wh L^{-1})	60-110	150-190	140-300	350-700
Battery voltage (V)	2.0	1.2	1.2	3.7
Cycle life (to 80% of the initial capacity)	300	1500	1000	500-2000
Self-discharge per month (%)	5	20	30	<10
Fast charging time (h)	8-16	1	1-4	1 or less
In use since	Late 1800s	1950	1990	1991
Toxicity	High	High	Low	Low
Overcharge tolerance	High	Moderate	Low	Low
Operating temperature range (°C)	−20 to 60	−40 to 60	−20 to 60	−20 to 60

Abbreviation: PEDs, portable electronic devices.
Values are taken from References 34 and 35.

consist of PbO_2 and Pb, respectively. The electrolyte turns back to concentrated H_2SO_4. Such a fully charged state stores most of the electrochemical energy.

Lead-acid batteries can be made in cylindrical or prismatic configurations (Figure 4). According to the immobilization of the electrolyte and O_2 recycle in the battery, lead-acid batteries can be divided into two types, that is, sealed lead-acid and valve-regulated lead-acid batteries. The sealed lead-acid battery is sealed entirely, while the valve-regulated lead-acid battery has a valve for releasing excess internal pressure. Moreover, the aqueous H_2SO_4 solution can either be soaked into an absorbent glass material or gel by addition of fumed SiO_2 in the valve-regulated lead-acid battery. The sealed lead-acid battery possesses the low capacity and thus is usually used in small-sized PED like portable radios.[34] The valve-regulated lead-acid battery has greater energy storage capacity and is commonly used as a stationary battery, for example, uninterruptible power sources, emergency lighting, and telecom powers. Besides, the valve-regulated batteries are also applied in high-power portable flood lights.

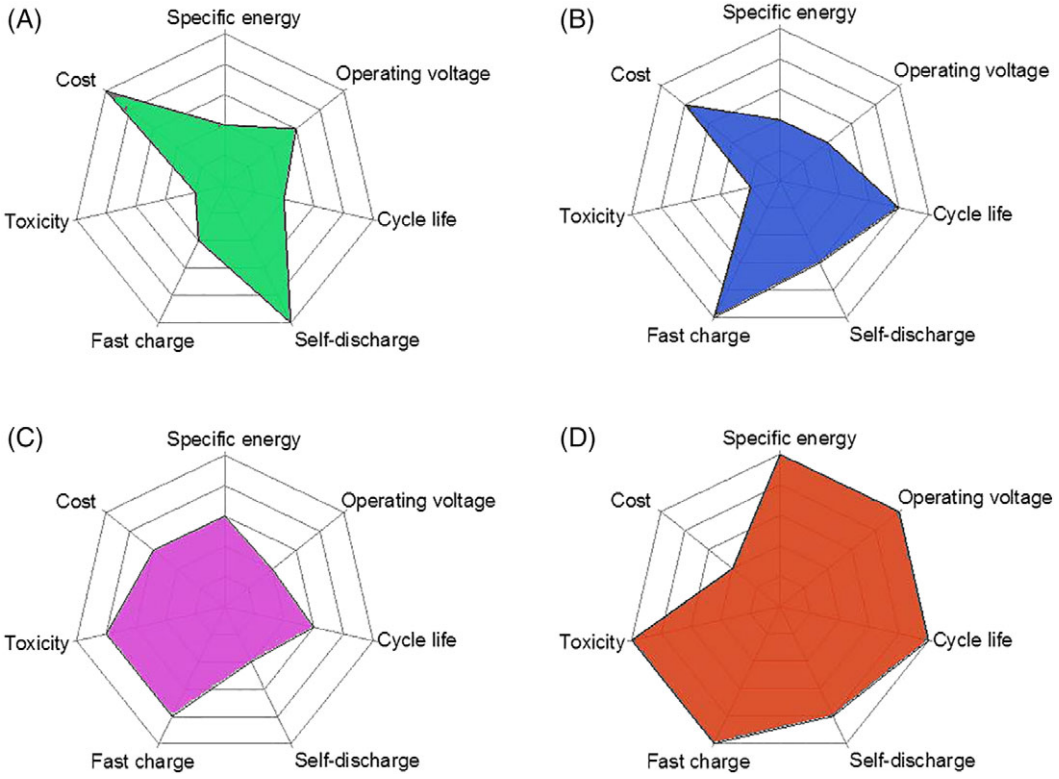

FIGURE 5 Performance comparison of A, lead-acid, B, Ni-Cd, C, Ni-MH, and D, Li-ion batteries

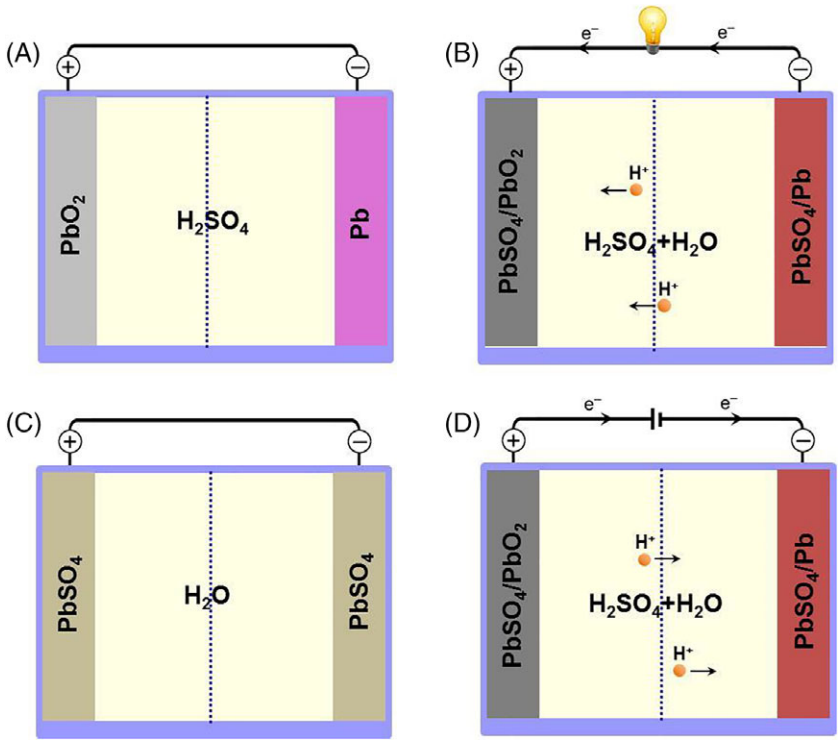

FIGURE 6 Schematic illustration of the lead-acid battery in different operational conditions: A, fully charged state, B, discharge process, C, fully discharged state, and D, charge process

In spite of their fascinating advantages, lead-acid batteries suffer several limitations, such as short lifetime (about 300-500 cycles), toxic for humans and the environment, and slow charge rates (Table 1). In particular, the main drawback of lead-acid batteries is their low gravimetric energy density of about 40 Wh kg^{-1}. They have the lowest specific energy storage capacity among Ni-Cd, Ni-MH, and Li-ion batteries, and usually, have a large size and heavyweight. This indicates that lead-acid batteries store the least amount of energy based on the battery weight, which limits their usability in small PEDs.

3.2 | Nickel-cadmium battery

The Ni-Cd battery was invented by Waldemar Jungner in 1899. It offers several advantages over the lead-acid battery, such as longer lifetime, attractive low-temperature performances, higher charge-discharge rates, and versatile in size ranging from small sealed portable types to large vented cells. Due to these exceptional characteristics, the Ni-Cd battery was once the dominant battery choice for both portable and standby power sources.

A Ni-Cd battery usually consists of NiO(OH) as cathode, Cd as anode, and KOH alkaline solution as electrolyte (Figure 7). Its operating principle is based on the redox reactions between NiO(OH) and Cd. The reversible electrochemistry reactions in a Ni-Cd battery are shown as follows:

$$\text{Cathode}: \quad \mathrm{NiO(OH) + H_2O + e^- \rightleftharpoons Ni(OH)_2 + OH^-}$$

$$\text{Anode}: \quad \mathrm{Cd + 2OH^- \rightleftharpoons Cd(OH)_2 + 2e^-}$$

$$\text{Overall reaction}: \quad \mathrm{2NiO(OH) + Cd + 2H_2O \rightleftharpoons 2Ni(OH)_2 + Cd(OH)_2}$$

Nickel oxide and Fe/Cd materials were used as the cathode and anode in the first Ni-Cd battery built by Jungner. Pure Cd metal and $Ni(OH)_2$ were used in subsequent Ni-Cd batteries. The development of the Ni-Cd battery was slow before 1932. In 1932, an important advancement was made by depositing the active battery materials inside a porous Ni-plated electrode. In 1947, the absorption of gases generated during the charge process promoted further improvements, leading to the modern sealed Ni-Cd battery. The widespread manufacture of this type of sealed Ni-Cd batteries began in the 1950s. From then on, the Ni-Cd battery occupied an overwhelming majority of the market as rechargeable batteries in various PEDs, including mobile phones, laptop flashlights, video cameras, and radios up to 1990s.

Nevertheless, one major drawback of Ni-Cd batteries is their memory effects, where their maximum energy capacity is gradually lost when they are not fully discharged before recharging or are not used for a while. Hence, Ni-Cd battery was often limited to electronic devices, such as mobile phones, which are frequently recharged after being only partially discharged. Another limitation of Ni-Cd batteries is their high self-discharge rate (Table 1). Besides, Cd is an expensive, heavy metal with high toxicity. Considering that a large number of PEDs were disposed every year, the

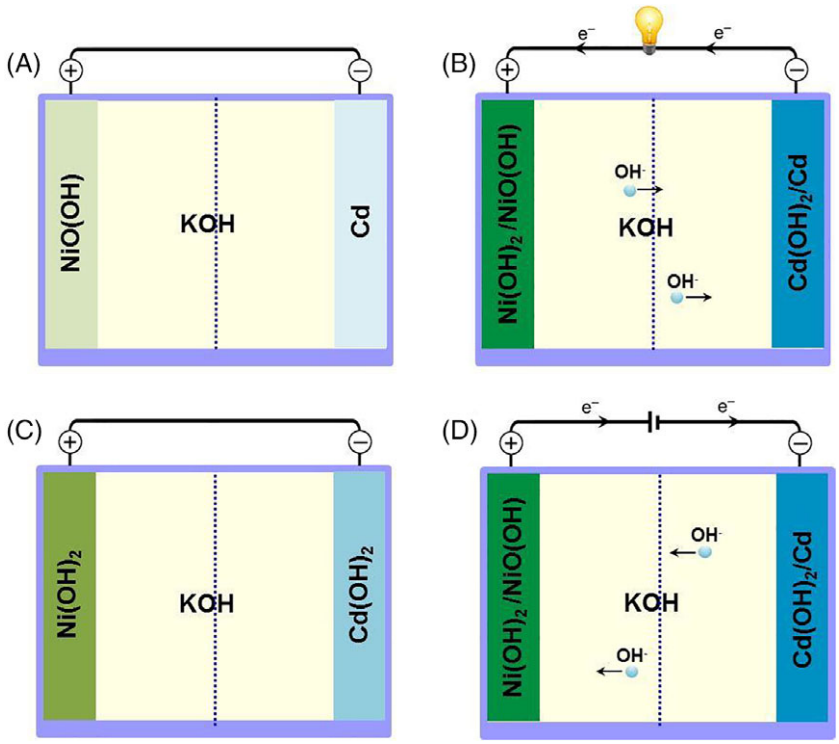

FIGURE 7 Schematic illustration of the Ni-Cd battery in different operational conditions: A, fully charged state, B, discharge process, C, fully discharged state, and D, charge process

abandoned Ni-Cd batteries also raise significant environmental concerns. Since the 1990s, Ni-Cd batteries gradually lose their popularity due to the development of Ni-MH and Li-ion battery technologies. Today, Ni-Cd batteries are only used for some specialty applications.

3.3 | Nickel-metal hydride battery

First patented in 1986 and commercially available in 1989, Ni-MH battery is an important type of rechargeable battery used in PEDs. Its configuration is very similar to that of Ni-Cd battery. They both use the same cathode materials and electrolyte, but instead of Cd, a hydrogen absorbing alloy is used as the anode in Ni-MH battery (Figure 8). As a result, the reversible electrochemistry reactions in a Ni-MH battery are shown as follows:

$$\text{Cathode}: \quad \mathrm{NiO(OH) + H_2O + e^- \rightleftharpoons Ni(OH)_2 + OH^-}$$

$$\text{Anode}: \quad \mathrm{MH + OH^- \rightleftharpoons M + H_2O + e^-}$$

$$\text{Overall reaction}: \quad \mathrm{NiO(OH) + MH \rightleftharpoons Ni(OH)_2 + M}$$

The replacement of metal Cd makes Ni-MH batteries less expensive and eco-friendlier when compared to Ni-Cd batteries. Besides, Ni-MH batteries have several other key advantages over Ni-Cd batteries, such as minimal memory effect, superior cycle life, excellent performances over a broader range of operating temperatures, high charge rates, and high energy density. Their energy density is more than two times that of lead-acid batteries, about 50% higher than that of Ni-Cd batteries, and even able to approach that of Li-ion batteries. The average cycle life can reach 500 cycles on a high-capacity Ni-MH battery and almost 3000 cycles on a low-capacity one. The Ni-MH battery also renders fast charge ability. For instance, it can be rapidly charged within 1 hour. Because of all these advantages, Ni-MH batteries soon replaced Ni-Cd batteries in PEDs and became the primary power solution in the early 1990s. Moreover, Ni-MH batteries have also been applied in commercial hybrid electric vehicles, such as Toyota Prius. However, in recent years, the usage of Ni-MH batteries has decreased significantly, mainly due to the development of Li-ion batteries and some of their disadvantages.

The largest drawback of Ni-MH batteries is their high self-discharge rate, which is up to three times higher than that of Ni-Cd batteries, and even more times higher than that of Li-ion and lead-acid batteries. For example, Ni-MH batteries would lose approximately a third of their stored charges in a month. This situation becomes even worse with the increasing operating temperature. Although the high self-discharge rate might be ignored in PEDs which are charged every day, this limitation poses severe problems for occasionally used PEDs.

3.4 | Lithium-ion battery

As the most commonly used rechargeable batteries nowadays, Li-ion batteries bring PEDs to a new age since 1991

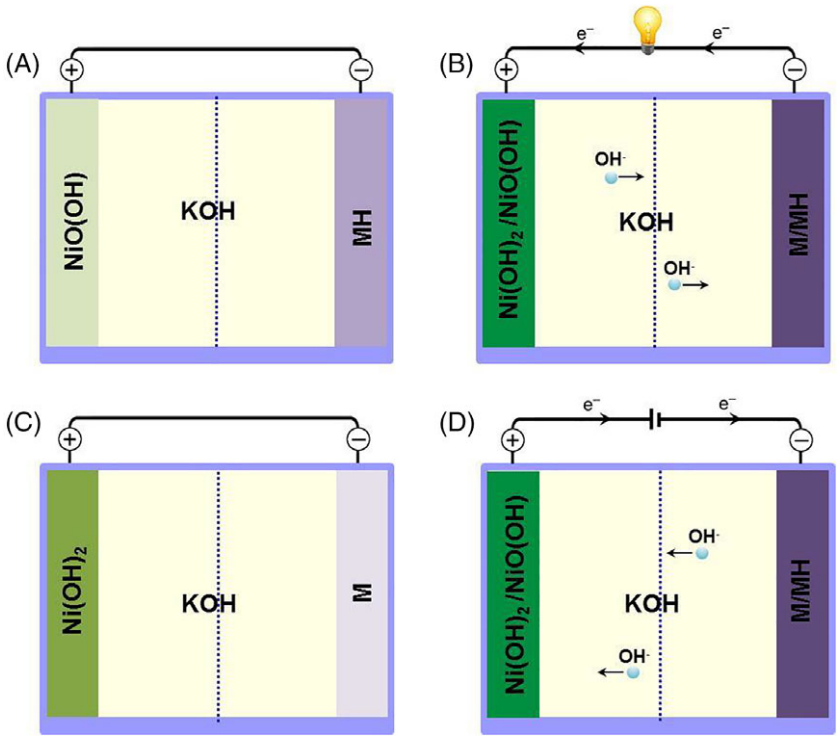

FIGURE 8 Schematic illustration of Ni-MH battery in different operational conditions: A, fully charged state, B, discharge process, C, fully discharged state, and D, charge process

when the Sony Corporation commercialized the first Li-ion battery. Their advent has been very challenging to other types of batteries, which could be ascribed to a number of advantages, such as high specific energy (typically twice that of standard Ni-Cd batteries), low self-discharge rate, high voltage of about 3.6 V (three times that of typical Ni-based battery), maintenance free, lightweight, good safety, and excellent cycling performance. These advantageous features make Li-ion batteries the best energy storage option for small-sized PEDs, such as mobile phones, laptops, digital cameras, and others, which was once dominantly by Ni-MH and Ni-Cd batteries. Meanwhile, Li-ion batteries are also growing in popularity for military, electric vehicle, and aerospace applications. More detailed information about the historical development of Li-ion batteries can be found in several excellent reviews.[33,36–38]

The electrochemistry reactions in Li-ion batteries are based on the intercalation and deintercalation of Li ions, in which Li ions move from the anode to the cathode during the discharge process and come back during the charge process (Figure 9). In a typical Li-ion battery, the anode is made of carbonaceous materials, that is, graphite. Metal oxides, such as Li cobalt oxides, Li iron phosphates, and Li manganese oxides are usually used as the main components for the cathode. Li salts, such as Li perchlorate, Li tetrafluoroborate, or Li hexafluorophosphate dissolve in organic solvents, such as diethyl carbonate, ethylene carbonate, or dimethyl carbonate, serve as liquid electrolytes for conventional Li-ion batteries.[39] When polymer electrolytes replace liquid electrolytes, the resulting batteries are called Li-ion polymer batteries. A high-conductivity gel containing lithium salts is often used as the polymer electrolyte. It should be mentioned that because of their thin and customizable shape, Li-ion polymer batteries are very attractive for PEDs, especially for ultra-slim laptops, mobile phones, tablets, and wearable electronic devices. To avoid confusion, Li-ion batteries containing liquid electrolytes are referred to as "liquefied Li-ion batteries" in the following discussion.

Li cobalt oxide ($LiCoO_2$) and graphite (C) are used as the representative cathode and anode materials, respectively, to describe the basic chemistry of Li-ion batteries. The reversible electrochemistry reactions are shown as follows:

$$\text{Cathode}: \quad LiCoO_2 \rightleftharpoons Li_{1-x}CoO_2 + xLi^+ + e^-$$

$$\text{Anode}: \quad C + xLi^+ + e^- \rightleftharpoons Li_xC$$

$$\text{Overall reaction}: \quad LiCoO_2 + C \rightleftharpoons Li_{1-x}CoO_2 + Li_xC$$

During the discharge process, Li ions move from the anode (ie, graphite) through the electrolyte and the separator to the cathode (ie, $LiCoO_2$). At the same time, electrons move from the graphite to the $LiCoO_2$. During the charge process, the reaction is reversed.

With the introduction of new materials and technologies, Li-ion batteries continuously improve their energy density, power density, lifespan, and safety.[40,41] However, Li-ion batteries are still suffering from some drawbacks. For instance, the higher manufacturing costs result in higher prices

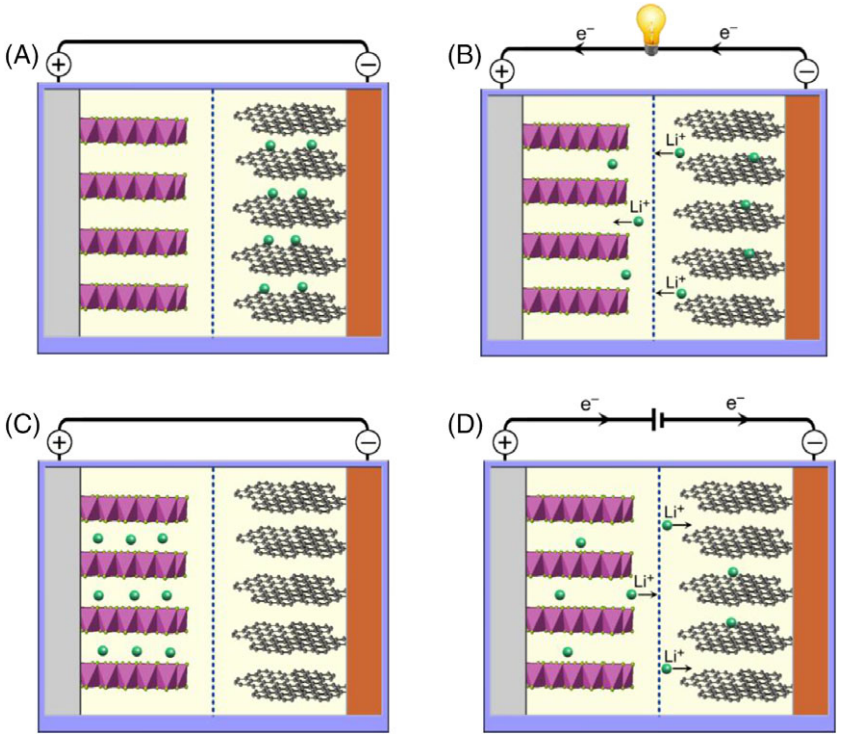

FIGURE 9 Schematic illustration of Li-ion battery in different operational conditions: A, fully charged state, B, discharge process, C, fully discharged state, and D, charge process

when compared with other rechargeable batteries. Although the price is getting lower year-by-year, Li-ion batteries still cost more than other competing batteries (Figure 5). Further, Li-ion batteries require additional protection circuits to limit voltages and currents to ensure safe operations. Besides, Li-ion batteries would lose their capacity and cycle life when are stored in temperatures over 30°C for an extended period. Nowadays, battery scientists and engineers are making significant efforts to address the drawbacks of Li-ion batteries.

4 | DEVELOPMENT OF RECHARGEABLE BATTERIES FOR PEDS

In this section, we briefly review the development process of rechargeable batteries for several types of PEDs. As detailed in this session, PED products continually being renovated at a faster speed since their birth, and the demands for better batteries are also explosively expanding.

4.1 | Traditional PEDs

4.1.1 | Mobile phones

The earliest mobile phone was Motorola's DynaTac 8000X released in 1983. It is commonly known as "Big Brother," and used a Ni-Cd battery with a small capacity of 500 mAh (Table 2). Such a battery provided the DynaTac 8000X a talk time of 20 minutes, but it took as long as 10 hours for recharging. In spite of this limitation, the number of the mobile phone sold each year increased rapidly. New mobile phone products were put on the market very quickly. In 1993, IBM launched the world's first smartphone "Simon." One year later, Nokia produced its landmark smartphone "9000." In 1995, Motorola launched the first flip mobile phone "8900." Ni-Cd batteries were the primary power sources for all these mobile phones. They accounted for almost half of the weight and volume of these mobile phones. Furthermore, as discussed above, Ni-Cd batteries suffered from memory effects. Those mobile phones using Ni-Cd batteries must be completely exhausted before recharging. Otherwise, the batteries would "remember" the shortened usage time and lead to power lost in less than 1 hour. Moreover, a long-time communication using mobile phones would lead to heat generation and eventually deform Ni-Cd batteries. In addition to the high toxicity of Cd, new rechargeable battery technology was urgently needed at that time.

In 1997, Ni-MH batteries were introduced to Motorola mobile phones "166C." Compared with Ni-Cd batteries, these Ni-MH batteries made remarkable improvements, for example, lighter, thinner, nontoxic, lower memory effect, and higher energy density. The energy storage capacities increased substantially from 500 to 700 mAh for Ni-Cd batteries to 1300 mAh for Ni-MH batteries (Table 2). The standby time of the mobile phones was extended to 50 hours. Ni-MH batteries became very popular in mobile phones. However, Ni-MH batteries exhibited serious self-discharge, which hindered their further adoptions in mobile phones.

The use of Li-ion batteries is a milestone in the mobile phone battery development. Without Li-ion battery, mobile

TABLE 2 Development of mobile phones and their batteries

Period	Historical stages	Representative product	Actual photo	Launch time	Battery type	Voltage (V)	Capacity (mAh)
1983-1993	Era of cellular phone	Motorola DynaTac 8000X (the world's first mobile phone)		1983	Ni-Cd battery	7.5	500
1993-1995	Miniaturization and intelligence	IBM Simon (the world's first smart phone)		1993	Ni-Cd battery	7.5	
		Motorola 8900 (the world's first flip mobile phone)		1995	Ni-Cd battery	6	950
1995-1997	Era of Ni-MH battery	Motorola 166C		1997	Ni-MH battery	6	1300
1998-2007	Era of popularization of mobile phone	Motorola GC87C		1998	Liquefied Li-ion battery	7.2	1200
2007-present	Era of new smart mobile phone	iPhone		2007	Li-ion polymer battery	3.7	1500
		Galaxy SIII		2012	Soft-pouch liquefied Li-ion battery	3.8	2100
		iPhone 6		2014	Li-ion polymer battery	3.8	1810
		Huawei mate 20p		2018	Li-ion polymer battery	3.82	4200

phones could not be shrunk from huge "bricks" to the size of pockets. Li-ion batteries are light weighted and have a higher energy density (30% higher than that of Ni-MH batteries), no annoying memory effects, and better safety. In 1998, Motorola started to produce mobile phones containing Li-ion batteries. From 1998 to 2000 is the transition period from Ni-MH to Li-ion batteries, when they fought nose-to-nose to gain customers' acceptance. It was not until 2001 that Li-ion batteries replaced Ni-MH batteries, due to the urgent needs of large energy storage capacity for multifunctional mobile phones and the reduction in the cost of Li-ion batteries. After 2002, Li-ion batteries have become the most promising battery technology for mobile phones. Since 2007, with the launch of Apple's iPhone, mobile phones entered the era of new smartphones. Various types of new mobile phones with more powerful functions were developed every year. They have increasingly become more than just devices for voice communications as they offer a multitude of features including connectivity, enterprise, and multimedia capabilities. Batteries with larger capacity are now demanded to satisfy the need of the increased safety requirement and power consumption by these new mobile phones. For example, the energy storage capacity of batteries used in the latest Huawei mate20p (Table 2) has reached 4200 mAh. The mobile phone industry is currently the largest consumer electronics segment in the world. With the rapid evolution of mobile phones, further advances in rechargeable batteries are expected for years to come.

4.1.2 | Laptops

The earliest portable computers appeared in the early 1980s. But their appearance is more like calculators. AA batteries or Ni-Cd batteries powered most of these portable computers, which can run for tens or even hundreds of hours because of their relatively limited functions (Table 3). The first laptop in the world is Toshiba T1100 released in 1985, which was still a big and bulky luxury without built-in batteries due to the limited performance of rechargeable batteries at the time. Since 1989, Toshiba led the portable computer industry by introducing laptops with built-in batteries. These laptops offered more computing power with thinner and smaller packages, which also demanded batteries with better performance. After 2 years of commercialization, Li-ion batteries were first

TABLE 3 Development of laptops and their batteries

Period	Historical stages	Representative product	Actual photo	Launch time	Battery type	Capacity (Wh)	Operating voltage (V)
1979-1984	Laptop prototype	Hewlett-Packard HP-110		1984	Lead-acid battery	15	6
1985-1994	Birth of laptop	Toshiba T1100		1985	Ni-Cd battery	19.2	4.8
1995-2005	Laptops entered the era of Li-ion batteries	Toshiba Portege T3400CT		1993	Cylindrical Li-ion battery	32.4	10.8
2006-2007	Apple laptop led the high-performance trend	Macbook Pro 2006		2006	Soft-pouch liquefied Li-ion battery	60	10.8
2008-2010	Birth of ultrabook	Macbook Pro 2008		2008	Li-ion polymer battery	60	10.8
2011-present	Popularization of ultrabook	Lenovo Yoga 13		2012	Li-ion polymer battery	54	14.8
		Lenovo YOGA 4 Pro		2016	Li-ion polymer battery	66	7.6
		Macbook Air 2018		2018	Li-ion polymer battery	49.9	11.4

introduced in the Toshiba laptop Portege T3400CT in 1993, which enabled a stand-by time of 6 hours.

With the introduction of a series of high-energy-consumption components in laptops, such as color display screens, high-performance CPUs, and independent graphics cards, the capacity of Li-ion batteries used in laptops increased significantly in the subsequent 10 years. During this period, the typical Li-ion batteries used in laptops were the cylindrical 18650 with a standard size of 18 mm in diameter and 65 mm in length, mainly due to their cost-to-energy ratio and ultra-thin geometry. A typical laptop battery pack comprised an average of approximately four to six such batteries to enable several-hour operation time.

The large-scale use of the 18650 batteries in laptops continued until Apple launched the MacBook series laptops. In 2006, Apple used soft-packed liquefied Li-ion batteries in MacBook Pro laptops to make them thinner.[42] In 2008, Apple switched to Li-ion polymer batteries in MacBook Air. Since then, Li-ion polymer batteries have been widely used in ultrabooks and other laptops (Table 3).

Currently, the portable computer market is trending toward thinner ultrabooks and tablets combined with high-end processors, which need to run complex programs while still require high responsiveness. Lenovo Yoga-series computers are one of the representative examples of the recent products of technological convergence. These crossover devices usually have a touch-screen display to allow consumers to work in a tablet mode, and then share traits of both laptops and tablets. All such devices are often very thin and light-weight. Accordingly, all of these developing trends in portable computers are driving the demand for even lighter, larger-capacity, safer, and longer-lifetime batteries.

4.1.3 | Digital cameras

The world's first digital camera was a laboratory product of Kodak in 1975 (Table 4). Later, Sony's Mavica was produced in 1981 as the first practical digital camera. These digital cameras used cylindrical batteries. The first commercial digital camera was Casio's QV-10 launched in 1995 (Table 4). Two AA batteries were used in this camera because its low-resolution pixels of 250 000 without a built-in flash. With the incorporation of built-in flashes and the increase in the pixel resolution, the requirement for high-capacity batteries continued increasing.

In 1998, digital single-lens reflex cameras appeared on the market. A considerable portion of these cameras used Ni-Cd or Ni-MH batteries. For example, Canon D2000 used

TABLE 4 Development of digital cameras and their batteries

Period	Historical stages	Representative product	Actual photo	Launch time	Pixel	Battery type	Capacity (mAh)
1975-1995	Test era of digital camera	Kodak's laboratory product (the world's first digital camera)		1975	10 000	16 series AA batteries	
		Mavica (the earliest practical digital camera)		1981	279 000	3 series AA batteries	
1995-1998	Commercialization of digital camera	Casio QV-10 (the first commercial digital camera)		1995	250 000	4 series AA batteries	
1998-present	Birth and popularization of digital single-lens reflex cameras	Canon EOS D2000		1998	2 000 000	Ni-Cd battery	1500
		Canon EOS D30		2000	3 100 000	Li-ion battery	1390
		Canon EOS5D		2005	13 300 000	Li-ion battery	1390
		Canon EOS R		2018	30 300 000	Li-ion polymer battery	1800

Ni-Cd batteries, while Nikon D1 used Ni-MH batteries. Afterward, Li-ion batteries became widely used in digital cameras along with the continuous improvement in their functions and the decrease in their volume. For example, Canon D30 appeared in 2000 used Li-ion batteries with a capacity of 1390 mAh (Table 4). Currently, most of the digital cameras have used Li-ion batteries, while some are still using standard AA batteries. Similar to other PEDs, digital cameras are getting smaller over the time, which leads to the increasing demand for batteries with lower volume and higher energy storage capacity.

4.2 | Emerging PEDs

With the expansion of human demands and the constant technological progress, the development speed of novel PEDs is continually accelerating. After the initial high-speed growth stage, the traditional PEDs discussed early have entered the phase of the stock competition. On the other hand, new PEDs, such as wearable electronic devices and consumer drones, are emerging. These new PED products offer multifunctionality, lightweight, integrability, and artificial intelligence (AI), are opening up broad market prospects, and are driving the continued growth of the whole PED industry. Correspondingly, their demands for innovative battery technology increase substantially. For example, flexible, smart, and wearable batteries are now desirable to power some of emerging wearable PEDs. In this section, the development of the emerging PEDs and their responding battery technologies are summarized.

4.2.1 | Wearable electronic devices

As the next hot spot in the PED industry, wearable electronic devices have been attracting more and more attention in both the academic research institutions and industry since Google launched Google Glasses in 2012.[43–46] Wearable electronic devices refer to clothing and accessories incorporating the body's sensing, communication, and digital entertainment functions. Typical examples include smart watches, smart glasses, smart clothing, heart rate monitors, fitness trackers, and so on (Figure 10). In general, they can be directly worn on the body or integrated into clothes or their wearable accessories, aiming at liberating human hands and enabling intelligent devices to meet people's requirements automatically.

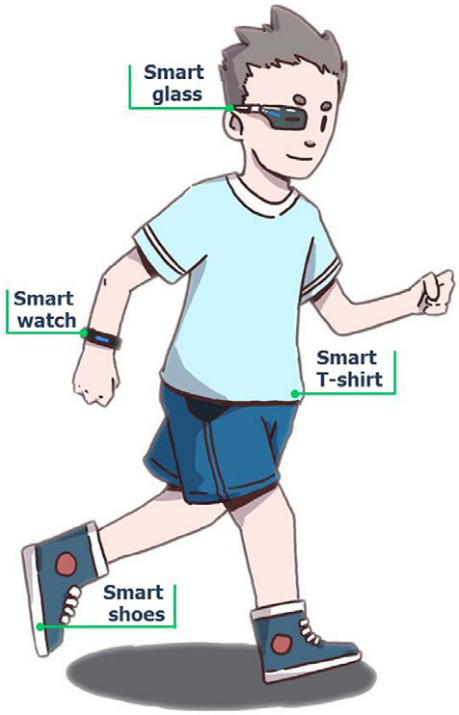

FIGURE 10 Schematic illustration of representative examples of wearable electronic devices

Consequently, wearable electronic devices are expected to improve the quality of human life further, and thus may play a significant impact on human daily routine and lifestyle, especially for healthcare, entertainment, and communication.

Wearable electronic devices, like other PEDs, need energy to operate. Wearable energy systems are a pivotal integral part of wearable electronic devices. On one hand, thin, small, and light are basic features of wearable electronic devices, which require their corresponding energy sources as small as possible. Conversely, the lifetime of power sources has a critical impact on the success of wearable electronic devices, as long endurance is the one of the first considerations for consumers in purchasing wearable electronic devices. However, it is challenging to meet these two requirements simultaneously due to the contradictions between size and capacity for batteries. Currently, rechargeable Li-ion batteries are the accepted energy storage choice for wearable electronic devices due to their advantages discussed previously.

Smart watches

A smart watch is a wearable computerized device intended to be worn on the wrist. Most of the current smart watches have multiple functionalities, such as long-term biomonitoring, calling, messaging, and altering, which are further communicating with mobile phone apps. Despite diverse features and designs, usage time is a major consideration for users, and users usually want to wear them all day long. Rechargeable Li-ion polymer batteries power most of smart watches. For example, Apple Watch uses built-in rechargeable Li-ion polymer batteries. Since Apple Watch Series 1 was released in 2015, the capacity of their batteries continuously increased from 205 mAh for Series 1 (with a 38 mm body) to 273 mAh for Series 2, to 279 mAh for Series 3 (Table 5).[47] Other Apple Watches with larger sizes offer slightly larger screens as well as batteries with larger capacity. It was reported that Apple designed these batteries for 18 hours of mixed usage.[48] When the battery capacity depletes to less than 10%, the watches convert to a power-saving mode, which enables consumers to read the time for an additional 3 days continuously. Despite these advances, the current battery life of smart watches is still falling short of the demands by consumers.

Smart glasses

Smart glasses, also known as smart eye wears, are ergonomically designed wearable computers that provide, collect, and process information alongside with what regular glasses do. Aiming at delivering a "hands free" digital world for wearers, smart glasses may be used in various modes, including optical head-mounted displays, heads-up displays, virtual reality, augmented reality, mixed reality, and smart contact lenses.[49] Wearers may also get access to Internet via voice commands, or take photos and record video by using a built-in high-definition camera.

Advanced power sources that can enable smart glasses to work for all day are essential for wearers' experiences. Rechargeable Li-ion polymer batteries power most of existing smart glasses due to their high gravimetric and volumetric energy density. Google Glass released in 2012 was powered by an internal Li-ion polymer battery with a capacity of 570 mAh, which can support the smart glasses for about 5 hours after a full charge.[50,51] This usage time may significantly reduce, depending on uses, configuration, mobile network, signal strength, and many other factors. The relatively small capacity battery was one of the major complaints of the original Google Glass. Recently, Google developed a Li-ion polymer battery with a higher capacity of 780 mAh for Google Glass Enterprise Edition to extend its run time.[52] Besides improving the capacity of incorporated batteries, the device usage time can be extended by external battery packs. For example, Vuzix M100 Smart Glass contains a 550 mAh internal rechargeable battery and a 3800 mAh external rechargeable battery. The internal battery delivers 2-hour run time, while the external battery increases the run time up to 6.5 times.[53]

Smart clothing

Smart clothing is gaining increasing popularity because they can effectively get targeted information by analyzing various wearers' biometrics and provide comprehensive feedbacks during daily life. Smart clothing is typically in the form of

TABLE 5 Development of wearable electronic devices and their batteries

Product type	Representative product	Actual photo	Launch time	Battery type	Capacity (mAh)	Battery life
Smart watch	Apple Watch Series 1		2015	Li-ion polymer battery	205	18 h with 90 time checks, 90 notifications, 45 min of app use, and a 30-min workout
	Apple Watch Series 2		2016	Li-ion polymer battery	273	Similar to Apple Watch Series 1
	Apple Watch Series 3		2017	Li-ion polymer battery	279	10 h of indoor workout 4 h of outdoor workout with GPS and 4G LTE
	Apple Watch Series 4		2018	Li-ion polymer battery	292	10 h of indoor workout, or 4 h of outdoor workout with streaming audio, GPS, and 4G
Smart glass	Google Glass		2012	Li-ion polymer battery	570	Less than 5 h
	Google Glass Enterprise Edition		2017	Li-ion polymer battery	780	About 8 h
	Vuzix M100		2014	Li-ion battery	550 (internal) and 3800 (external)	6 h of hands free, or 1 h of hands free, display, camera, and high CPU loading (for internal battery)
	DPVR P1		2018	Li-ion polymer battery	3000	About 4 h
	HiAR G100		2017	Li-ion polymer battery	2700	4 h of AR experience
Smart clothing	OMsignal smart T-shirt		2014			16-30 h of intensive workout time, or 3-4 d of continuous wear
	Nike Mag shoes		2011			3000 h
	Xiaomi Mi smart shoes		2017	Li-ion battery	210	60 d
	Digitsole Smartshoe		2016	Li-ion polymer battery		A couple weeks with heat off, or 5-8 h with heat on
	Samsung WELT belt		2016	Li-ion polymer battery	90	20 d

Abbreviation: AR, augmented reality.

wearable shirts, socks, windbreakers, sportswear, shoes, belts, and other textiles. Similar to other types of wearable electronic devices, smart clothing incorporates digital components (eg, sensors, small computers, and other electronics) to provide added functions, such as monitoring wearers' physiological and behavioral data. To power smart clothing, built-in batteries are needed. High safety and reliability have made Li-ion polymer batteries as a reasonable energy storage solution for clothing. For example, OMsignal smart T-shirt's built-in battery can operate for 16 to 30 hours of intensive workout time, or 3 to 4 days of continuous wear without recharging.[54] Nike Mag shoes were released in 2011 as the first rechargeable footwear featured by the electroluminescent out-sole and space-age materials, which consists of a rechargeable internal battery for a total usage time of 3000 hours.[55]

4.2.2 | Consumer drones

As unmanned aerial vehicles, consumer drones are aircrafts without a human pilot aboard for civilian usages. In recent years, the general public has developed a strong interest in consumer drones, consequently creating an unprecedented boom in the new consumer drone industry. It is estimated that the global shipment of consumer drones would reach 8.34 million by 2020. The potentials of consumer drones are endless. Currently, they are widely used in aerial photography. With the continuous progress in technology and decrease in cost, consumer drones are increasing being applied to power patrol, movie-video shooting, mobile communication, meteorology monitoring, and express delivery. DJI is the worldwide leader in the consumer drone industry, which accounts for more than 70% of the world market.[56] In addition to DJI, EHANG, Parrot, and 3D Robotics are also known for launching powerful consumer drones (Table 6).

Unlike other unmanned aerial vehicles used in military operations that often use combustion engines or solar cells, consumer drones typically run on electricity. Consumer drones rely on a reliable power source to achieve an ideal balance between performance and flight time. The most commonly used power sources are Li-ion polymer batteries (Table 6) because of their high specific volumetric energy storage density, high power density, and long life in comparison with other rechargeable batteries.

The voltage and capacity of used batteries play significant roles in the flight performance of consumer drones. The battery voltage has an important impact on the maximum motor speed. A higher voltage provides greater motor spinning speed. The voltage of single standard full-charged Li-ion polymer batteries is 3.7 V. Multiple Li-ion polymer batteries are usually connected in series as battery packs to increase the voltage outputs. The standard battery packs are in 1S, 2S, 3S, 4S, 5S, or 6S configurations, where "S" refers to connected in series. A 2S battery pack can deliver 7.4 V. Because of the optimized balance between motor speed and battery weight, battery packs in the 4S configuration is the most commonly used for consumer drones.

The battery capacity is often used to reflect how long a battery can supply energy at a particular current. For example, a battery with a capacity of 3000 mAh may supply a 3 A current for 1 hour, or a 6 A current for half an hour, and so on. Batteries with higher capacity may provide longer flight time, but their weight also becomes more burdensome. The increase in weight restricts the response performance of drones. Therefore, a balance is needed between the battery capacity and the weight. In typical consumer drones, the capacity of batteries with a mass of about 200 g ranges from 3000 to 4000 mAh. Such consumer drones can fly about 15 to 25 minutes under normal conditions, that is, without heavy wind or cold weather. But the flight time is substantially reduced with fast responses and high mobility. For example, a racing drone with a 1300 mAh battery can fly only about 3 minutes. Larger batteries with a capacity up to 2200 mAh would be required to achieve a longer flight time of 5 to 8 minutes.

5 | DEVELOPMENT TRENDS OF BATTERY TECHNOLOGIES FOR PEDS

Although rechargeable batteries have transformed PEDs over the past decades, insufficient battery performance is still the bottleneck of emerging PEDs. Comparing the rapid process in electronics, the improvement in batteries is much slower and shows a sign of reaching a performance plateau in recent years. Thus, developing new high-performance batteries to meet the demands of emerging PEDs remains a critical issue. In recent years, considerable research efforts have been devoted to improving existing rechargeable batteries and developing new batteries. Significant advances have been attained in increasing energy density, improving safety, lowering cost, and enabling mechanical flexibility. The development trends in these aspects are discussed in the following sections.

5.1 | Increasing energy density

The task of increasing battery energy density has driven the entire battery technology progress over the past two decades. Up to date, battery energy density remains the primary criteria in selecting a battery system for PEDs, which is especially crucial for PEDs because of the limited space and weight allocated for batteries in PEDs. However, the advances in increasing

TABLE 6 Development of consumer drones and their batteries

Company	Representative product	Actual photo	Launch time	Battery type	Capacity (mAh)	Operating voltage (V)	Battery weight (g)
DJI	Mavic Pro		2016	3S Li-ion polymer battery	3830	11.4	240
	Mavic Air		2018	3S Li-ion polymer battery	2375	11.55	140
	Mavic 2		2018	4S Li-ion polymer battery	3850	15.4	297
	Spark		2017	3S Li-ion polymer battery	1480	11.4	95
	Phantom 4 Pro		2016	4S Li-ion polymer battery	5870	15.2	468
	Phantom 3 SE		2017	4S Li-ion polymer battery	4480	15.2	365
	Phantom 4 Advanced		2017	4S Li-ion polymer battery	5870	15.2	468
ZEROTECH	DOBBY		2016	2S Li-ion polymer battery	970	7.6	65
FLYPRO	XEagle		2016	3S Li-ion polymer battery	5200	11.1	370
EHANG	GHOSTDRONE 2.0		2017	4S Li-ion polymer battery	4500	14.8	400

battery energy density fail to keep up the pace of growing demands by PEDs. Although Li-ion batteries exhibit the highest energy density among various rechargeable batteries, their energy density, ranging from 170 to 250 Wh kg^{-1} or 350 to 700 Wh L^{-1}, is still not able to cope with the increasing energy storage requirements by emerging PEDs (Figure 11).[2,58] Therefore, it is a worldwide and urgent desire to further increasing the energy density of rechargeable batteries.

Since batteries' specific capacities and operation voltages determine their energy density, increasing these two parameters has been the primary research targets.[35,59,60] Currently, the research efforts for improving the energy density of rechargeable batteries can be classified into two categories. Methods in the first category focus on optimizing existing rechargeable batteries, including their electrode materials, electrolytes, separators, binders, current collectors, and battery

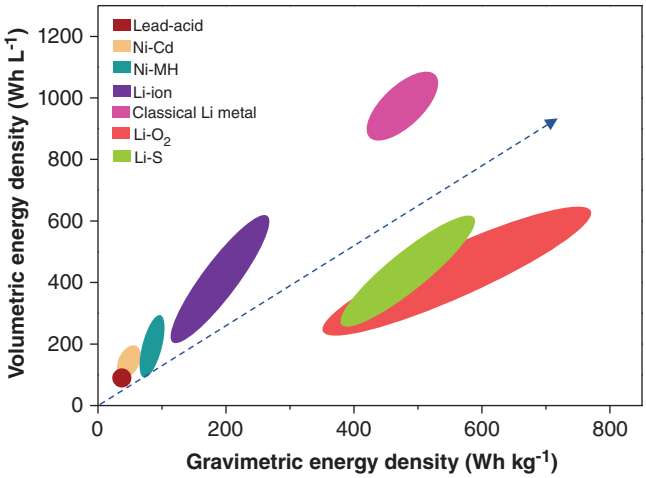

FIGURE 11 Gravimetric energy density vs volumetric energy density plot of various types of rechargeable batteries. Values are taken from References 7 and 57

manufacturing techniques (eg, increasing the packing densities and the mass ratios of active electrode materials in assembled batteries). For instance, graphite is the common anode material for commercial Li-ion batteries due to its good stability, excellent conductivity, and high Coulombic efficiency. However, the theoretical Li storage capacity of graphite anodes is only 372 mAh g^{-1}.[61–64] Many other materials with higher Li storage capacities, such as Si (4200 mAh g^{-1}),[65,66] Sn (994 mAh g^{-1}),[67–69] SnO_2 (782 mAh g^{-1}),[70,71] Fe_2O_3 (1007 mAh g^{-1}),[72] MnO_2 (1232 mAh g^{-1}),[73] Co_3O_4 (890 mAh g^{-1}),[74] and NiO (718 mAh g^{-1}),[75–77] have been explored as new anode materials. Similarly, traditional cathode materials (eg, Li cobalt oxide, Li iron phosphate, and Li manganese oxide) can be substituted by large-capacity materials (eg, Ni-rich layered oxides and Li-rich layered oxides)[78–80] or high-voltage materials (eg, polyanion oxides and spinel materials).[2,81,82] These efforts have been able to significantly improve the energy density of Li-ion batteries at least in many research lab studies.

Methods in the second category focus on developing new batteries. It has been speculated that existing batteries, including Li-ion batteries, have limited room for further improvement. A breakthrough in increasing the battery energy density requires developing new electrochemical reactions.[83–89] Along this line, new battery systems have been intensively pursued in recent years, including Li metal batteries,[90–96] metal-sulfur batteries,[97–104] metal-air (or metal-oxygen) batteries,[105–109] and batteries involving monovalent (eg, Na and K)[110–115] or multivalent (eg, Mg, Ca, Zn, and Al) elements/cations.[116] Among various new battery systems, Li-sulfur, Li metal, and Li-oxygen batteries have gained great attraction due to their exceptionally high energy density (Figure 11). In particular, Li-sulfur and Li-oxygen batteries have the theoretical gravimetric energy density of 2600 Wh kg^{-1} and 3500 Wh kg^{-1}, respectively.[117–119] Researchers hope that they can deliver a practical battery energy density of 2 to 5 times higher than those of current Li-ion batteries.[120–122]

Nevertheless, it should be noted that these new batteries are still far from mature. There are many technical challenges in translating research lab findings to scalable industrial production.[37,123,124] Significant research and development efforts are required to make them competitive with the existing state-of-the-art Li-ion batteries for practical PED applications.

5.2 | Improving safety

Batteries present a safety risk since they store a large amount of chemical energy in a small space, and thus they are prone to fire or explosions if operated improperly. Batteries used in PEDs are particularly dangerous to human due to their frequently carry-on characteristics. There have been numerous incidents related to fires and explosions of batteries worldwide, especially involving mobile phones, laptops, and electric vehicles.[125] For instance, the United States Federal Aviation Administration have reported over 206 air/airport battery fire/explosion incidents from 1991 to 2018.[126] The battery problems of Boeing 787 Dreamliner and Samsung Note 7 have attracted worldwide attention. It is highly desirable to better manage safety issues for new batteries used in emerging PEDs.

The reasons of battery fire/explosion incidents vary, which may include short circuits, mechanical abuses, battery overcharging, or manufacturing defects.[127] Numerous methods have been proposed to improve battery safety. These methods can be divided into external or internal protection approaches.[128] External protection approaches are usually using additional external devices. For example, using temperature sensors and pressure valves to monitor batteries under thermal or pressure abused conditions.[126] These technologies are relatively mature, which are not discussed in details here.

Internal protection approaches focus on introducing intrinsically safe components to different components of batteries. First, chemical additives are added to electrolytes. These chemical additives usually comprise flame-retardants,[129–133] ionic liquids,[134–136] shut-down, and redox shuttle additives.[137,138] Second, some other chemical components are used to achieve stable electrode/electrolyte interfaces.[139,140] Third, solid-state batteries based on either polymer gels or inorganic electrolytes have also been explored as internal protection approaches.[141–152] Polymer gel electrolytes can improve battery safety because less organic solvents are used without leakage. Further, inorganic solid ceramic electrolytes (eg, $Li_7La_3Zr_2O_{12}$, $Li_{14}ZnGe_4O_{16}$, and $Li_{3x}La_{2/3-x}TiO_3$) or glass-ceramic electrolytes are attractive because they are nonflammable, low-cost, no leakages, and stable against high

TABLE 7 Main characteristics of lithium, sodium, and zinc elements

Characteristics	Lithium	Sodium	Zinc
Price ($ kg^{-1})	~120	~3	~3
Specific capacity (mAh g^{-1})	3860	1166	820
Capacity density (mAh cm^{-3})	2061	1129	5855
Voltage vs S.H.E. (V)	−3.040	−2.713	−0.763
Ionic radius (Å)	0.76	1.02	0.75

Abbreviation: S.H.E., standard hydrogen electrode.
Values are partially taken from References 207 and 208.

temperatures.[153–161] Besides, the mechanical rigidity of solid ceramic electrolytes suppresses the formation of Li dendrites, which is a major reason for battery short circuits. Forth, the optimization of separators,[8,162–167] current collectors,[168] anode materials,[89,169–172] and cathode materials[173–175] may also improve the safety of batteries. Detailed discussion on these optimizations can be found in a recent review.[128] It should be noted that these internal protection methods are more frequently used in Li-ion batteries, because of the high reactivity of materials utilized in Li-ion batteries. In general, Li-ion batteries pose higher safety risks compared to other rechargeable batteries discussed in this review.

5.3 | Lowering cost

Batteries used in PEDs must meet challenging cost targets to achieve commercial success. Li-ion batteries have successfully dominated today's PED battery market. However, because of their higher cost (normally 300 $ kWh^{-1} whereas 90 $ kWh^{-1} for lead-acid batteries), many efforts have been made to reduce the cost of Li-ion batteries through material designs and synthesis, battery manufacturing, and packaging. These efforts fall into two categories.

The first category involves lowering the cost of various battery components (ie, cathodes, anodes, electrolytes, separators, binders, and current collectors) or reducing manufacturing costs of batteries.[24,26,176] The cost of battery materials is closely related to their synthesis process and the price of raw materials. Over the past decades, great efforts have been devoted to developing new eco-friendly

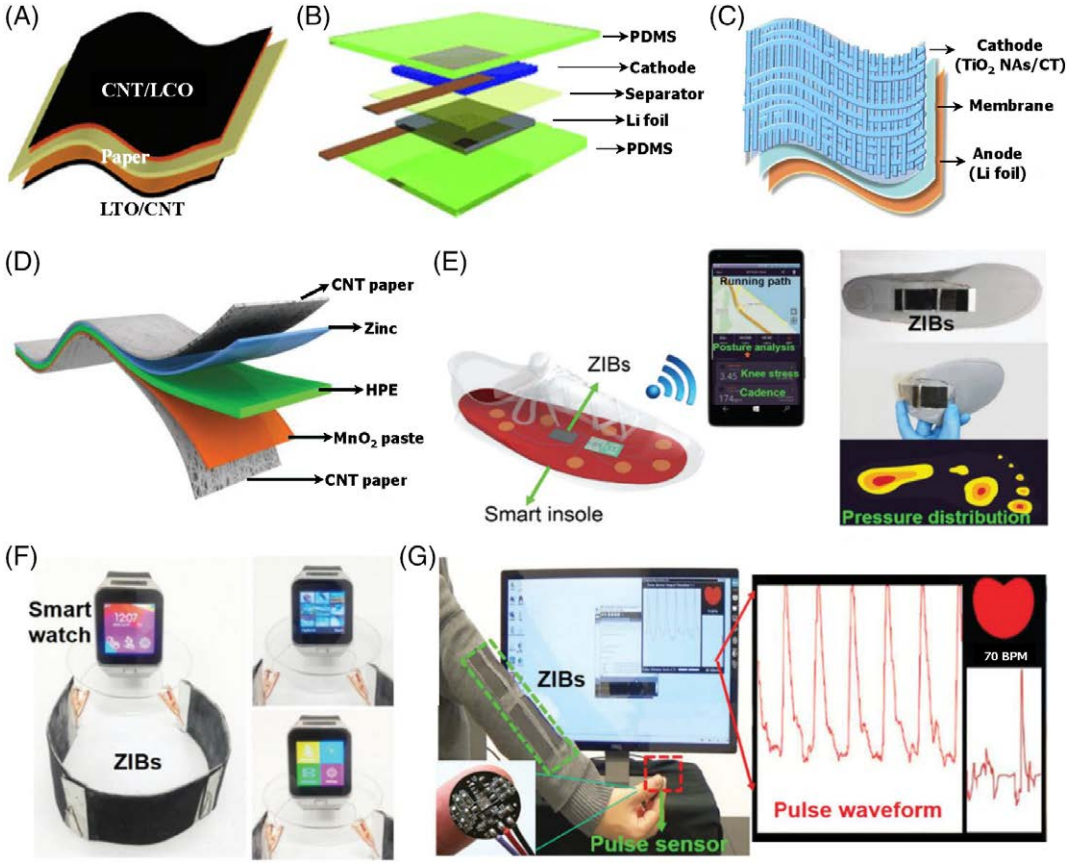

FIGURE 12 A, Schematic illustration of a flexible Li-ion battery. Reproduced with permission.[234] Copyright 2010, American Chemical Society. B, Schematic illustration of a flexible Li-sulfur battery. Reproduced with permission.[235] Copyright 2015, Wiley-VCH. C, Schematic illustration of a flexible Li-oxygen battery. Reproduced with permission.[236] Copyright 2015, Nature Publishing Group. D, Schematic illustration of a flexible Zn-ion battery. Wearable applications of flexible Zn-ion batteries in E, a smart shoe, F, a smart watch, and G, a pulse sensor. Reproduced with permission.[223] Copyright 2018, Royal Society of Chemistry

routes to synthesize battery materials[177–185] and exploring sustainable battery material substitutes.[177,186–190]

The second category focuses on developing cheaper batteries to replace Li-ion batteries. Because of the limited availability and uneven distribution of Li in the world, alternative metal-ion batteries using earth-abundant metal elements, such as Na-ion,[191–193] Zn-ion,[194–196] K-ion,[197–199] Mg-ion,[200–202] and Al-ion batteries,[203–206] have been studied. For instance, Na accounts for 2.64% of the earth's crustal reserves, which is 4 to 5 orders of magnitude higher than Li. Besides, Na is widely distributed and easy to extract, thus resulting in a lower price (Table 7). Similar circumstances can be found for Zn and other elements. Despite great efforts and significant progress made in research labs, many issues have to be overcome to enable these new battery systems to be cost competitive alternatives to Li-ion batteries.

5.4 | Enabling mechanical flexibility

Wearable electronic devices, especially those with mechanical flexibility (eg, roll-up displays), represent a new direction for the electronics industry.[2,209–213] Further, they may be combined with wearable sensors (eg, smart clothing) to revolutionize the human's life. Strong consumer demands are driving the development of such flexible devices. Some flexible electronics are already available on the market, for example, the FlexPai and Samsung Infinity Flex. Flexible rechargeable batteries have become an active research area in the last few years to meet the energy storage requirements in these flexible devices.

To date, various types of flexible batteries including flexible Li-ion,[214–218] Li-sulfur,[219–221] Li-air,[210,222] Zn-ion,[223–226] and Zn-air[12,227–233] batteries have been demonstrated. As shown in Figure 12, some of them have exhibited attractive potentials for PEDs. Despite these achievements, substantial technical challenges remain. The electrochemical functions of flexible batteries usually deteriorate under long-term frequent mechanical deformations, for example, bending, folding, twisting, and other strain modes.[237] One critical task is to create flexible electrodes with high capacity, fast charge/discharge capability, and excellent cycling stability, which can be further coupled with flexible electrolytes and separators.

6 | CONCLUSIONS AND PERSPECTIVES

PEDs are important platforms for realizing efficient information collection, processing, and dissemination. They have experienced a rapid growth during the previous three decades. The performance of these PEDs has been becoming more and more sensitive to their energy consumption, which relies on their energy storage components, that is, batteries. The ever-increasing demands for high-performance batteries drive the progresses of commercial battery devices from lead-acid to Ni-Cd, to Ni-MH, and to Li-ion batteries. The advances in battery technology, in turn, promote the continuously reinventing of the PED products to promote our lifestyle changes. For instance, since the birth of the first cellular phone in 1993, the mobile phones were upgraded every 2 years on average, which is closely related to the remarkable process in rechargeable battery technologies. In order to further satisfy the continually high requirements of rechargeable batteries in PEDs, significant research efforts worldwide have been devoted to improving existing battery systems using new materials, advanced techniques, and emerging energy chemistries. Furthermore, many new battery systems are also being explored. Although most of recent findings in research labs are far from large-scale practical applications, in our view, the following directions can open up new frontiers based on multidisciplinary scientific investigations.

The current exploration on the energy storage system enables sustainable developments of the battery technology with enhanced specific energy, better safety, and lower cost, especially under the drive of vast demands from PED and electrical vehicle industry. Among various new battery technologies, Li metal-based batteries, sodium ion batteries, as well as those rechargeable batteries with solid electrolytes are particularly regarded as promising energy storage systems in the future to replace the current batteries. These next-generations of advanced batteries will facilitate the development of new information devices to continuously push it forward. With the progress in the rechargeable battery technology, more and more multifunctional PEDs are highly anticipated in the near future.

The trend for the development of the state-of-the-art rechargeable battery technologies requires a precision match between the requirements of the devices and the electrochemical indicators of energy storage process, which is also a long-pursued goal for the customized design of batteries for specific applications. To realize this point, it is highly important to establish better marriages among materials, functionalities, applications, and their innovations. The targeted research activities in such fields can help to efficiently develop key information energy materials, and thus further promote the progress of the PEDs.

The current hot topic on AI is the coming innovative direction in the field of materials science. AI is able to not only quickly analyze data to deduce general characteristics of advanced materials, but also filter all possible composition combinations to precisely predict new compositions and potential properties that can be used for predesigned application areas. In this regards, AI provides a new and promising tool for the innovation of advanced battery materials, including electrode materials, electrolytes, separators, and other

components. Consequently, the introduction of AI can significantly increase the rates of creating advanced energy materials when compared to those conventional methods through highly frequent experiments in the lab. With these efforts, the performance and cost-effectiveness of battery technologies are expected to be remarkably optimized in a short time. Meanwhile, the considerable growth of the energy storage technologies not only guarantees the continuous operation of AI equipment, but also meets their future requirements of ever-increasing energy consumption.

Information energy material is a rising point of interdisciplinary. More efforts are required to be highly multidisciplinary between scientists and engineers in the fields of chemistry, material science, computer, mathematics, physics, and engineering. Such interactions should be explored systematically from both theoretical and experimental aspects to boost the progress. These explorations can shed new lights in the improvement of electrochemical performance for the coming battery technologies, which will bring more cheerfulness to our future life.

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CONFLICT OF INTEREST

The authors have no conflict of interest to report.

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