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Evaluation of the Optimistic Use of Renewable Energy by Best Utilization of Rechargeable Batteries

Dr. Hossain K A*

Vice Chancellor, Bangladesh Maritime University, Dhaka, Bangladesh

***Corresponding Author:**
Dr. Hossain K A Vice Chancellor, Bangladesh Maritime University, Dhaka, Bangladesh

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Abstract
Electrochemical energy storage has been instrumental in the technological evolution of human societies in the 20th century and continues to play an important role today. Electrochemical storage systems could be seen as a subgroup of chemical energy storage systems; they are sufficiently distinct from the four energy forms described herein that they can be given a separate class. Electrochemical energy storage and conversion systems, such as electrochemical capacitors, batteries and fuel cells, are considered the most important technologies proposing environmentally friendly and sustainable solutions to address rapidly growing global energy demands and environmental concerns. Their commercial applications individually or in combination of two or more devices, are based on their distinguishing properties e.g., energy/power densities, cyclability and efficiencies. In this review article, we have discussed some of the major electrochemical energy storage and conversion systems and encapsulated their technological advancement in recent years. Fundamental working principles and material compositions of various components such as electrodes and electrolytes have also been discussed. Furthermore, future challenges and perspectives for the applications of these technologies are discussed.

Keywords: LiBs, SiBs, Energy Storage Systems (Esss), Renewable Sources Of Energy, Electrochemical Energy Storage And Conversion Systems (Eecss), Future Prospects

Introduction
With the increasing severity of climate change and the threat of global warming, countries are accelerating the development and promotion of renewable energy sources like solar and wind to bring about the energy transition and reduce carbon emissions. Every society depends on electrical power to meet its fundamental requirements. On the other hand, carbon dioxide emissions have drastically increased, leading to global warming. The current situation has jeopardized the environment in which people reside, leading to abnormal rainstorms, prolonged droughts, and an accelerated expansion of desert areas. Long-term variations in weather and temperature conditions, including differences in solar activity and significant volcanic eruptions, are referred to as climate change. Human activity has served as the primary cause of global warming since the beginning of the 19th century. Carbon emissions must be reduced by nearly 50% by 2030 and reach net-zero levels by 2050 to avert the worst effects of climate change. The creation of diverse renewable energy sources is one potential course of action. According to predictions from the International Renewable Energies Agency (IRENA), by 2050, 90% of the world's electricity could and ought to originate from renewable sources. Utilizing renewable energy sources to the fullest can help reduce air pollution and related health problems. By using the force of nature to create electricity, marine energy, wind energy, and solar energy are significant types of renewable energy that reduce carbon dioxide emissions and reduce global warming [1-4].

Electrochemical energy storage technology is one of the cleanest, most feasible, environmentally friendly, and sustainable energy storage systems among the various energy technologies, namely mechanical storage, thermal storage, electrochemical storage, and chemical storage. Electrochemical energy storage/conversion systems include batteries and ECs. Despite differences in energy storage and conversion mechanisms among these systems, a common electrochemical feature is that the reactions occur at the electrode/electrolyte phase boundary near the two electrodes. Batteries store energy via chemical interventions (Faradaic reactions/redox reactions) at the anode and cathode. The anode is the negatively charged electrode, whereas the cathode is the positively charged electrode. Faradaic reactions can be reversible/irreversible, but battery materials often involve irreversible chemical reactions. The irreversibility has caused limitations of battery cycle life to one thousand to several thousand charge-discharge cycles, which vary based on the battery type and the electrodes employed. Batteries are closed systems where the anode and cathode active materials play a prominent role in the redox reactions to store and convert energy [5-9].

Electrochemical energy storage is a highly effective means of alleviating the growing energy and environmental crises. Among electrochemical storage options, lithium-ion batteries (LiBs) and sodium-ion batteries (SiBs) with high performance and lost cost show very broad application prospects. However, the design and manufacture of suitable electrode materials with ideal performance is the primary challenge for these batteries' achieving performance improvement. Therefore, enormous efforts have been made to explore electrode materials for LiBs and SiBs to realize the requirements of large-scale commercial applications. Recently, two-dimensional (2D) transition-metal carbides, nitrides, and carbonitrides (collectively called MXenes) have been paid much attention for their unique properties, such as high electrical conductivity, rapid molecule and ion transport, low operating voltages, and high storage capacities.

Technologies provide energy security, lessen the negative effects on the environment and human health, and lessen reliance on fossil fuels. Renewable Energy power led to inconsistent power output and compromised grid security. The energy storage battery system can react rapidly to variations in frequency and voltage, keeping the grid stable. The primary benefit of rechargeable battery technology is the capacity to effectively store and release electrical energy. These are making it appropriate for a range of applications, particularly in electric vehicles and grid regulation. Because of its adaptability, broad range of applications, and ability to maintain power stability amid significant changes in renewable energy sources, this technology is garnering attention. Rechargeable batteries are multipurpose power sources that can be repeatedly utilized and charged by an external voltage. Lead-acid batteries, nickel-metal hydride batteries, batteries with lithium ion (including lithium cobaltite and manganate), and nickel-cadmium batteries are common varieties. Rechargeable batteries have become a cost-effective and environmentally responsible choice because of their high energy density, safety, dependability, protection against the environment, and longer cycle life. They are extensively utilized in high-power, continuous-use gadgets, including electric toys, power tools, and mobile phones. Rechargeable battery power is not without its issues, though. Rechargeable batteries, for instance, may overheat when being charged or discharged, which could lead to leakage and a short circuit. The battery's performance can also be reduced by improper operation, overcharging or draining, particularly with a power battery, and improperly timed charging or errors during operation [10].

Rechargeable batteries are devices that can store and release electrical energy after multiple charging and draining cycles. The functioning principle is based on electrochemical processes. It stores electrical energy when charging and releases it during discharging using electrodes and electrolytes. Batteries usually consist of a positive electrode, a negative electrode, and an electrolyte. Metal oxides or phosphates are common positive electrode materials. Graphite and lithium metal are common materials for negative electrodes. Electrolytes are liquids, gels, or solids that allow ions to travel among electrodes. When a battery is charged, electrons and ions flow from the negative electrode to the positive electrode, and the reverse occurs during discharge. This process can be repeated on multiple occasions, and it is the irreversible electrochemical reaction that enables the battery to both charge and discharge. Rechargeable batteries use electrochemical reactions to transfer chemical energy to electrical energy. During the discharge process, an oxidation reaction happens at the anode (negative electrode), releasing electrons and delivering power to an external circuit; are duction reaction occurs at the cathode (positive electrode), taking electrons. When charging, an external power source enables electrons to flow back, restoring these chemical processes and restoring the battery's capacity.

However, because these energy sources are unreliable in terms of supply, efficient energy storage technologies are required to balance energy output and satisfy daily electricity demand. Among numerous energy storage alternatives, rechargeable battery technology has received a lot of interest due to its high energy density, efficiency, and reusability. Currently, lithium-ion batteries, nickel-metal hydride batteries, lead-acid batteries, and other rechargeable battery types are widely utilised in consumer electronics, transportation, renewable energy storage, medical equipment, and other industries. This study will evaluate the elementary operating principles, structure, and important chemical composition of rechargeable batteries, along with performance measures such as capacity, energy density, cycle life, technology's global applications, development status and major challenges, including safety, cost, longevity, and environmental impact, etc. This study will further discuss probable future technology innovations, market trends, and suggestions which will help to formulate suitable policies needed to be implemented in the near future. So, it is an effort to evaluate the optimistic use of renewable energy by best utilization of rechargeable batteries.

Literature Review

Electrochemical energy storage technologies, especially rechargeable batteries, have been the backbone of PED operations for quite some time, and this has helped fuel their stratospheric ascent to fame. To keep up with the ever-growing needs of PEDs, rechargeable batteries have seen substantial improvements in their electrochemical characteristics. A wide variety of rechargeable batteries have been included into PEDs, including lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion, and many more. Over time, their unique energy and power levels significantly improve. Current battery technology cannot keep up with the rapid expansion of PEDs. The growth of personal electronic gadgets is hindered by the constraints of modern rechargeable batteries, which include a short cycle life, a rapid self-discharge rate, and a poor energy storage capacity. Multipurpose personal electronic devices (PEDs) have a significant power consumption and need more powerful, smaller, lighter, and longer running period energy storage systems. Existing battery capacity is being tested as the demand for new electrical and electronic gadgets continues to rise. As a result, innovative battery design and manufacture have been the focus of future PEDs [11-20]. Improving batteries' electrochemical capabilities has been a major focus of research. Recent studies have shown that substantial progress has been. Numerous high-quality assessments also address the evolution of battery technology. Nevertheless, reviews that cover all aspects of PED rechargeable batteries are few and far between. The growth of personal electronic devices (PEDs) has been greatly influenced by battery technology; thus, it is fascinating to look back at how these batteries have changed over the last several decades. A timeline portraying the evolution of electronic components from static to dynamic has been shown in figure 1 below [21-31].

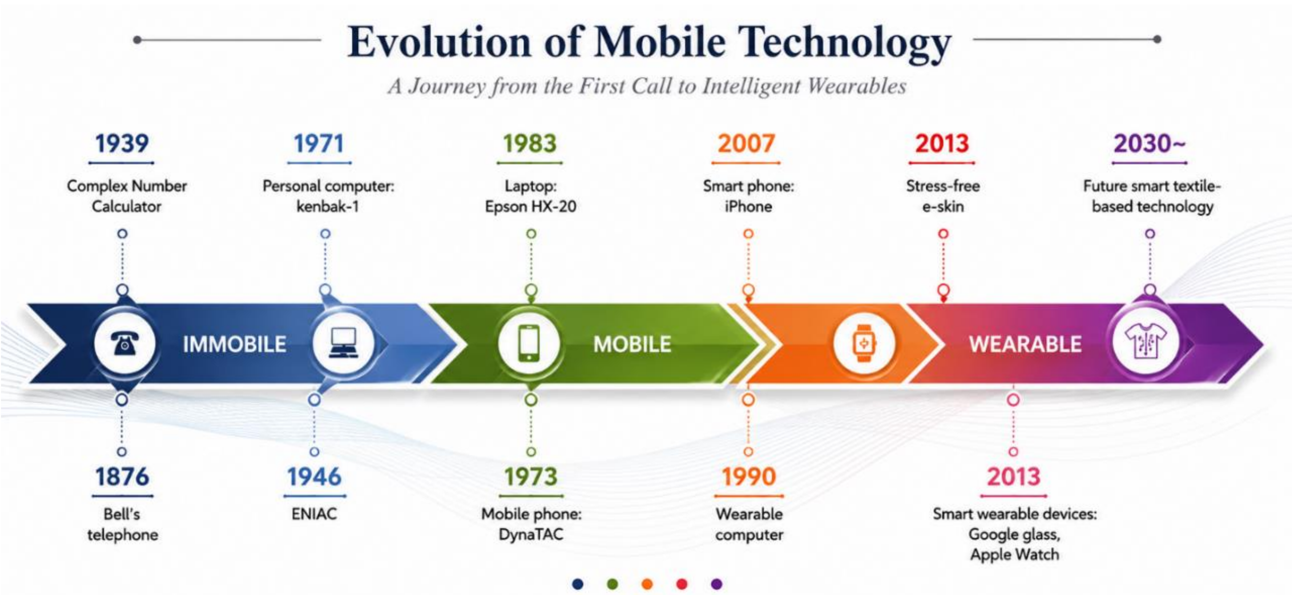

Figure 1: A Timeline Portraying the Evolution of Electronic Components From Static to Dynamic [32]

Traditionally, new battery technologies have been developed via iterative cycles of intuition-based study, experimental trial and error, and, sometimes, fortunate discoveries. The development of battery systems is becoming more complicated, thus new approaches are clearly required to keep up with the pace of innovation and facilitate the rapid translation of research into marketable goods. In the past, researchers have relied on intuition and experimental trial and error to create new batteries, with the help of accidental discoveries along the way. At the same time, new methods are obviously needed to understand the growing complexity of battery system development and to swiftly commercialize findings from laboratories. M. Stanley Whittingham, Akira Yoshino, and John B. Goodenough were awarded the 2019 Nobel Prize in Chemistry for their contributions to the development of the lithium-ion (Li-ion) battery throughout the 1970s and 1980s. Moving away from the potentially dangerous lithium metal anodes and toward the safer rechargeable metal oxides and carbon materials, Sony released the first Li-ion battery to the market in 1991. The key historical developments researchable battery has describe below [33,34].

- An early researcher on electrochemical batteries was an Englishman named Stanley Whittingham, who was employed by Exxon during the 1970s oil crisis. He took a risk by creating the first rechargeable lithium battery, which used lithium metal as the anode and titanium disulfide (TiS_2) as the cathode.

- In 1980, John B. Goodenough from the University of Oxford discovered that using lithium cobalt oxide ($LiCoO_2$) as the cathode of a battery might potentially triple its energy potential and safety.

- In 1985, a stable anode was created by Akira Yoshino, a Japanese scientist who collaborated with Asahi Kasei. They achieved this by replacing metallic lithium with petroleum coke, a carbonaceous material. The battery's safety and its ability to be commercialized were both enhanced by this invention.

- Sony introduced the world to the first commercially available lithium-ion battery in 1991. This innovative method completely changed the game for portable electronic power sources; it achieved great energy density using a graphite anode.

- Rechargeable Li-ion batteries revolutionized handheld electronics in the 1990s. They first appeared in Sony's Handycams and then spread to other electronic devices.
- The focus shifted in the 2000s and remains on electric cars (EVs) and renewable energy storage. The industry has shifted to using Li-ion batteries because to their greater performance, higher energy density, and lower production costs.

Rechargeable batteries that store energy via the reversible intercalation of lithium ions into solid materials that are electrically conductive are known as lithium-ion batteries, or Li-ion batteries. Among the many features that distinguish Li-ion batteries from competing commercial rechargeable batteries are their extended cycle life, high specific energy, excellent energy efficiency, and lengthy calendar life. Also worth mentioning is the incredible progress made in lithium-ion battery technology since its introduction. The 2019 Nobel Prize in Chemistry recognized the discovery and widespread use of lithium-ion batteries, one of the most momentous technical advancements in human history. Electronic vehicles, portable electronics, computers, mobile phones, and cellular networks are all part of the e-mobility revolution that Li-ion batteries have made feasible. As for the tenth, they find extensive use in grid-scale energy storage, aircraft, and the military [35,36].

The first rechargeable lithium-ion battery, created by M. Stanley Whittingham in the 1970s using the idea of intercalation electrodes using a lithium-aluminum anode and a titanium disulfide cathode, was never mass-produced due to safety concerns. Using lithium cobalt oxide as the cathode, John Goodenough enhanced this method in 1980. One kind of rechargeable battery is the lithium-ion battery, or Li-ion battery abbreviation LIB. Modern Li-ion batteries, which use a carbonaceous anode instead of lithium metal, were initially prototyped by Akira Yoshino. The military and aerospace industries are rapidly expanding their use of lithium-ion batteries, which are already ubiquitous in electric vehicles and other portable electronics. In the 1970s, people like Akira Yoshino, Rachid Yazami, Stanley Whittingham, Robert Huggins, and John Goodenough began to make significant advancements in the field. Asahi Kasei and Sony were able to commercialize these innovations in 1991 because to these discoveries that persisted throughout the 1980s and allowed for advances in understanding. The 2019 Chemistry Nobel Prize in Chemistry was to Goodenough, Whittingham, and Yoshino for developing lithium-ion batteries. Lithium ions go from the negative to the positive electrode of a battery via the electrolyte when the battery is discharged or charged. In most Li-ion batteries, graphite makes up the negative electrode and intercalated lithium compounds the positive one. Aside from having a high energy density, the batteries don't have any memory effect. In a lithium-ion battery, the four primary components are the electrolyte, separator, cathode, and anode. All of these parts work together to move lithium ions, which store and release energy.

The enormous growth in world population, particularly in the developing world, coupled with technological developments, is considered the key factor behind the immense increase in electrical energy consumption over the past half-century. Further increases in global energy consumption are expected, with energy demand projected to double by the middle of the century and triple by the end of the century as a result of continued population growth with the world population expected to reach 9 billion by 2048 and increased electricity demand in the industrial and commercial sectors. Currently, fossil fuels such as oil, gas, and coal are the primary energy sources, with more than 85% of the world's total energy generation coming from these conventional sources. Over-reliance on fossil fuels for the production of energy has led to numerous environmental challenges including poor air quality, unexpected climatic variations, water/soil contamination and a colossal increase in greenhouse gas emissions. To contain or reverse these trends, the deployment of more sustainable, low-carbon, or even carbon-free renewable energy sources, such as wind, solar, or tidal, is essential. However, these renewable energy sources are location-specific and, in some cases, unpredictable, and therefore operational flexibility is key to their integration into power systems. This flexibility is attainable when using appropriate energy storage technologies that can help in managing fluctuations and mismatches in energy supply and demand, ultimately improving the efficiency of energy and power supply systems by reducing the gap between production and consumption [37-41].

Moreover, growth in energy proportion added to the national grid through the integration of renewable sources such as wind and solar results in curtailments, which can be addressed by using appropriate storage technologies. There is a broad range of energy storage and conversion technologies available, including chemical, thermochemical, mechanical, electrical and electrochemical storage systems. Among these, electrochemical energy storage and conversion systems such as electrochemical capacitors/batteries and fuel cells, respectively, have received the most intensive attention and have been adopted in everyday applications due to their high columbic efficiencies. Fundamentally, energy storage devices perform two important tasks like, time shifting bulk energy from renewables production to the time of energy demand or supplied by batteries + fuel cells. Another task is, production of clean, stable power and frequency, avoiding voltage spikes and that is important for the digital economy by supercapacitors and high-power batteries. However, challenges related to their durability, high cost, environmental concerns, and operability must be addressed in order to improve their effectiveness and further increase uptake. For instance, even though lithium-ion batteries have transformed the technology of electric vehicles (EV) and portable electronics such as mobile phones and laptops, this technology still suffers from issues such as high lithium cost and safety concerns. In 2011, almost 78% of lithium was extracted from brines in Chile, Argentina and USA, and the rest came from hard rock mines (in China and Australia). Environmental impact of lithium mining including human health, effect on biodiversity and availability of clean/fresh water for consumption and agricultural use are other key concerns. Since major lithium reserves are located in salt lakes and pans where lithium is extracted through evaporation and flooding of reserves with fresh water. Similarly, electrochemical capacitors (ECs) have inferior energy densities whereas fuel cells have operability and system issues [42-47].

Development of Portable Electric Devices

There has been enormous growth and advancement in PED products since they first came out as shown in figure 2 above. Particularly booming are sales of the so-called "3C" products: computers, communications, and consumer electronics. As an example, the mobile phone industry has recently become the undisputed king of consumer electronics worldwide. As shown in Figure 3A, the global shipping of mobile phones increased from 9.6 million in 2003 to 1536 million in 2017. Two key factors have contributed to the exponential growth of PED products. Consumer desire for more sophisticated data collection and handling technologies is driving the fast expansion of the PED business. The dizzying rate of technological progress also drives the constant introduction of new PED products. Take mobile phones as an example. On average, new models are released every two years since Big Brother, the first cellular phone, was introduced in 1993. Technological developments in semiconductors and other electrical components have played a pivotal role in this. The tremendous growth of electric vehicles and renewable energy storage is tied directly to advancements in Lithium-ion batteries. Over three decades, energy density tripled while costs dropped tenfold, allowing industries to scale away from fossil fuels. Historical development of telecommunication devices from Telegraph to smart wearables has been shown in figure 3 below. There is a tight relationship between this explosive growth and the creation of innovative battery technology. With the advent of Li-ion batteries in 1991, a plethora of portable electronic devices (PEDs) using these batteries have proliferated. These include mobile phones, laptops, digital cameras, Walkman, MP3 players, tablets, and, most significantly, the ever-present wearable electronic gadgets. Newly launched PED items have the potential to open up markets that are rapidly expanding. Their expansion will slow down when the market is completely saturated.

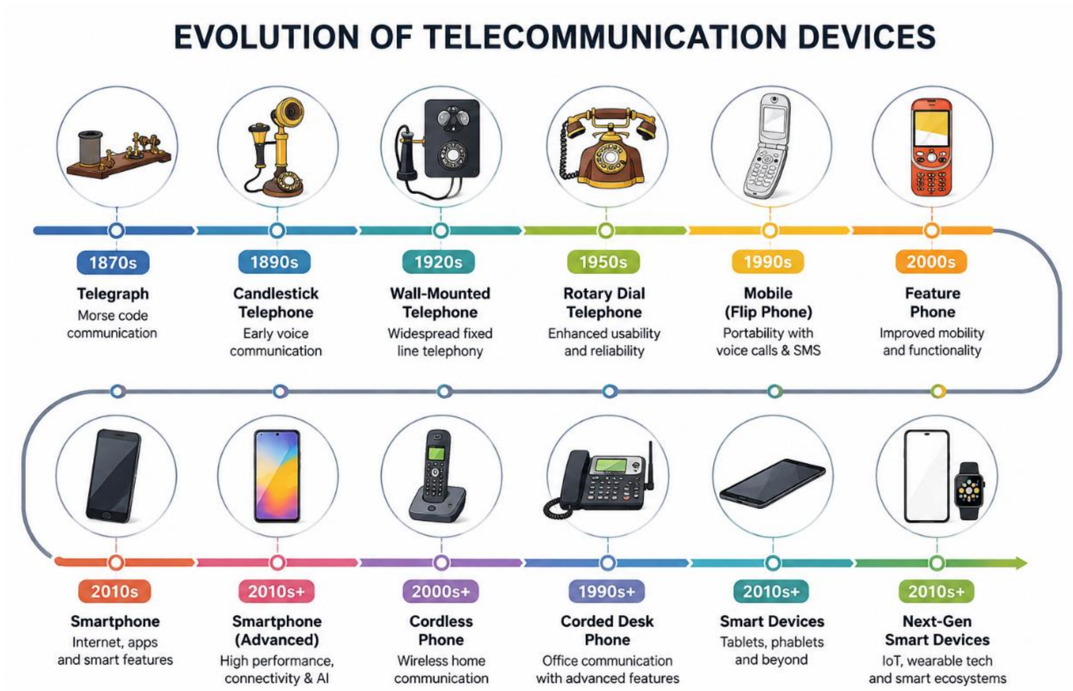

Figure 2: Historical Development of Telecommunication Devices From Telegraph to Smart Wearables

We can give example, growth in the traditional PED product industry, which encompasses devices like laptops, smartphones, and tablets, and that has slowed to a trickle. From 680 million in 2012 to 1536 million in 2017, the total number of mobile phones supplied globally increased, despite a fall of 44.8% to a growth of 2.7% and that has been shown in Figure 4A below. On the other hand, the prolonged use of laptops is the main reason why the market for these devices has been declining since 2012, and 2015 saw a significant decline of 10.4 percent and that has been shown in Figure 4B. Again, both the tablet and digital camera markets are seeing negative growth, and those have been shown in Figures 3C and 3D respectively below. The global tablet market has been on a downward spiral since 2015, with a 15.5% year-on-year decline in 2016 to 175 million units sold. However, because to their high yields and extensive market penetration, the overall number of traditional PEDs is rapidly expanding. In figure 4 A and B show that, laptops and mobile phone have positive growth. Whereas figure show in 3C and D have proved tablet and digital camera respectively have negative growth. However, the global shipping numbers for 2018 are based on the first six months of that year. In that sequence, Wind, IDC, Gartner, and mobile phones are the sources of data for digital cameras, computers, tablets, and smartphones. Global shipments and growth rates pattern of (A) mobile phones, (B) laptops, (C) tablets, and (D) Digital cameras have been shown in figure 3 A, B, C and D respectively [48,49].

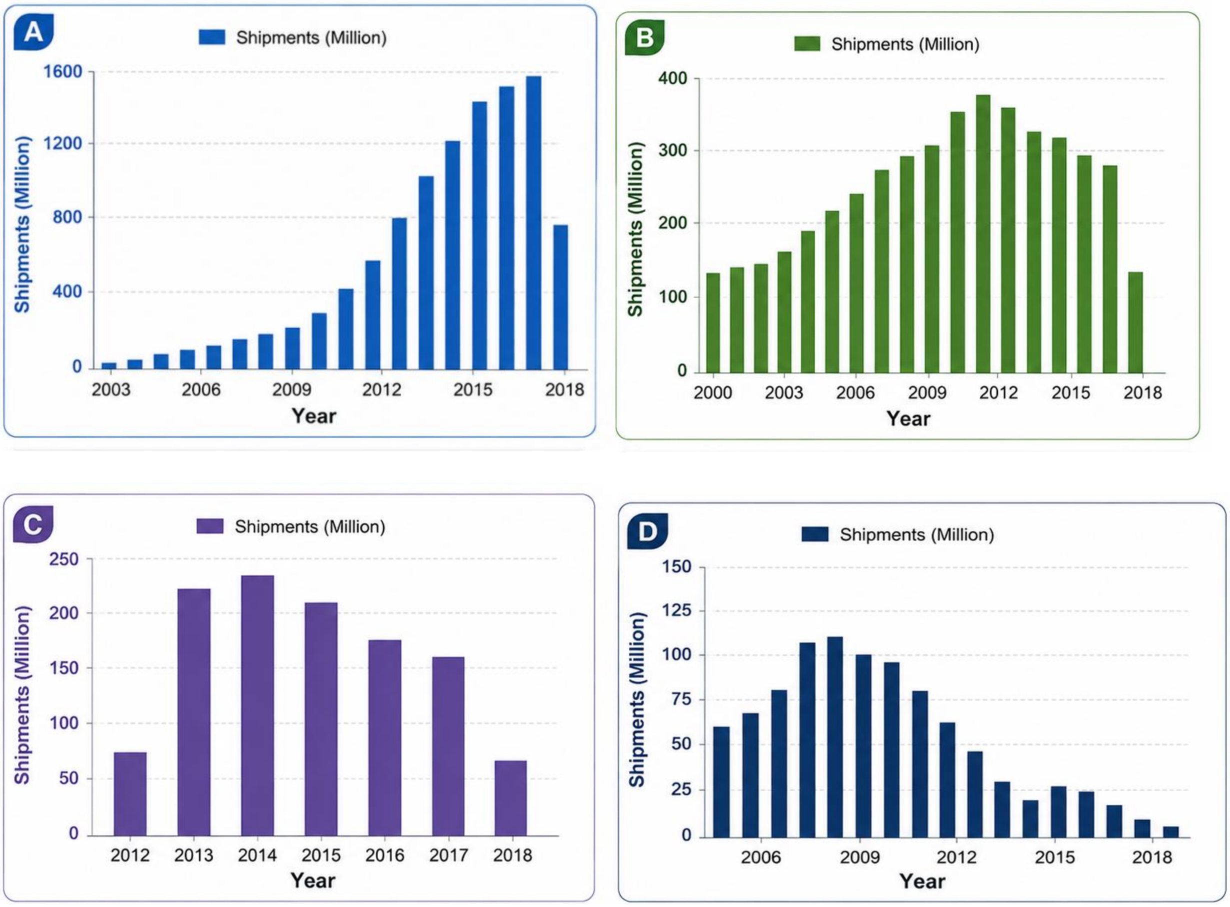

Figure 3: Global Shipments and Growth Rates Pattern of (A) Mobile Phones, (B) Laptops, (C) Tablets, and (D) Digital cameras

The smartphone is one of the big consumers of costly and sophisticated Li-ion battery. The global smartphone market refers to the global industry connecting the production, distribution, and sales of smartphones. It includes different players like manufacturers, suppliers, and technology providers. The industry is highly competitive, driven by innovation and consumer demand for better technology, features, and designs. The Global Smartphone Market size is expected to be worth around USD 939.2 Billion by 2033, from USD 539.5 Billion in 2023, growing at a CAGR of 5.7% during the forecast period from 2024 to 2033 and that has been shown in figure 4 below. The emergence of new PEDs, such consumer drones, wireless Bluetooth speakers, wearable electronic devices, and comparable items, has been a major driver in the PED industry's growth. The global market for wearable electronics, for instance, is seeing meteoric expansion, driven mostly by the increasing demand for fitness trackers and smartwatches. The global shipment of wearable devices topped 78.1 million in 2015, marking a rise of 172.6% from 2014 to 2015. Forecasts indicate that by 2020, the global shipment of wearable gadgets would reach 214 million, with an annual growth rate of 20.3%. The market for consumer drones is another promising new field. There was a substantial increase in the shipment of consumer drones between 2013 and 2015. Forecasts indicate that consumer drone shipments will reach 3.1 million units globally by 2018 [50,51].

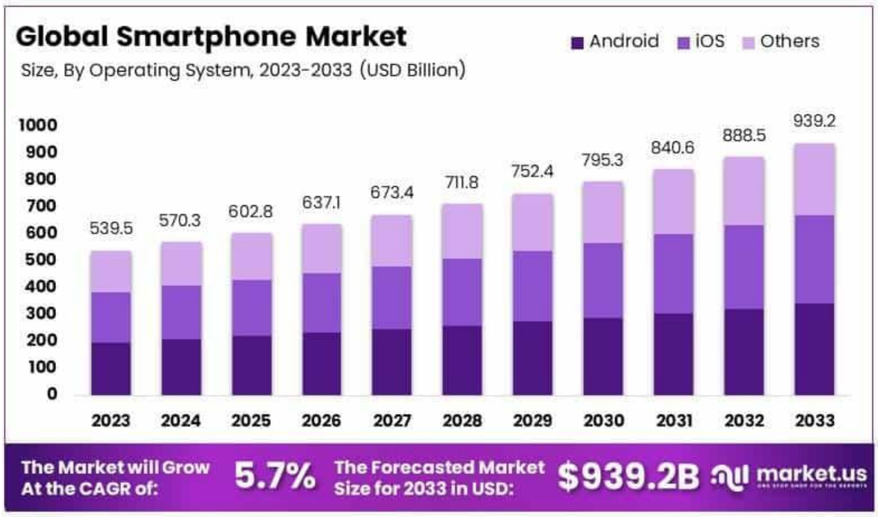

Figure 4: Growth of Global Smart Phone Market [52]

Types of Rechargeable Battery Technology for 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. To satisfy the continually high requirements of PEDs, significant improvements in electrochemical performances of rechargeable batteries have been attained. Improving rechargeable battery technology is crucial to the fast development of PEDs. Primary batteries have long served as the de facto standard for powering PEDs. The development of rechargeable batteries at the turn of the century, however, has caused a sea shift due to their increased energy and power density. The vast majority of modern consumer electronics use rechargeable batteries. The evolution of PEDs coincided with the incorporation of several rechargeable battery types, including lead-acid, nickel-cadmium, nickel-metal hydride, and lithium-ion batteries. Figure 5 shows in below are the four most frequent forms of these rechargeable batteries: coin, cylindrical, prismatic, and pouch. Two types of batteries have been around for a long time: lead acid and nickel cadmium. Although Li-ion batteries weren't invented until 1909, Ni-MH batteries were first produced in 1859. It may be said that both of these battery kinds are relatively new. The AI picture of important and common feature of different rechargeable batteries have been shown in figure 6 below [53-55].

Figure 5: The AI Picture of Common Configurations of Rechargeable Batteries: (A) Coin, (B) Cylindrical, (C) Prismatic, And (D) Pouch

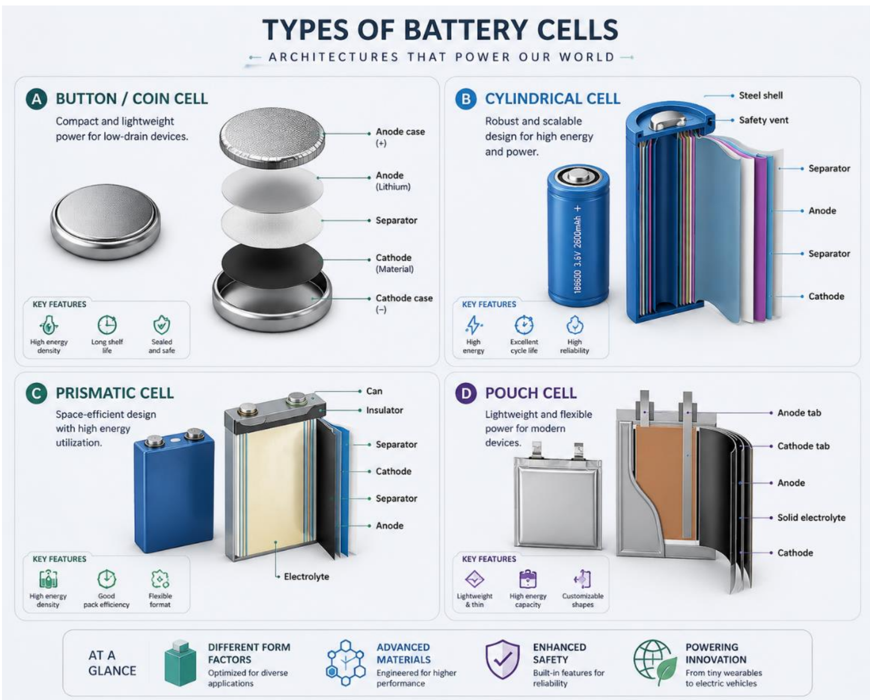

Figure 6: The AI Picture of Important and Common Feature of Different Rechargeable Batteries

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. 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 go on. For example, 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 have 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 innovations and efforts. The development of Ni-MH and other lithium-ion batteries has paved the way for their extensive application in portable electronic devices (PEDs). Graph drown by AI to explain the efficiency of four different types of batteries: A, lead-acid, B, nickel-cadmium, C, Lithium-ion and Solid -state has been shown in figure 8 below. On the other hand, the basic four battery types are compared in Table 1 and Figure 7, which show their key qualities and important features. After this quick introduction, we'll go into the specifics of each of these battery kinds and how they have aided in the development of PEDs in the recent history [56-58].

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

Table 1: Features of Four Main Categories of Ped Rechargeable Batteries

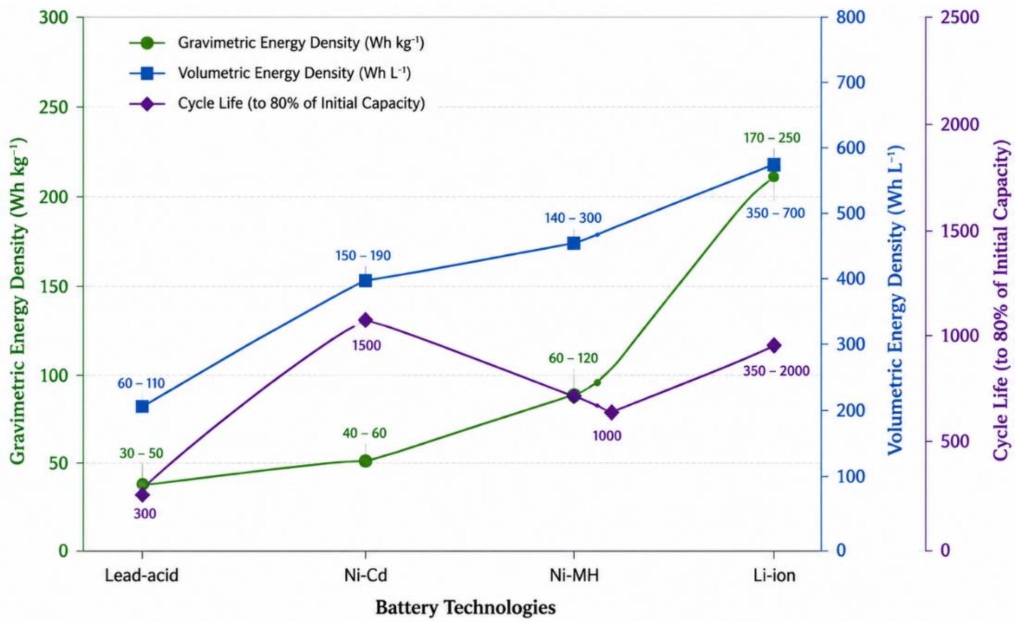

Figure 7: Features of Four Main Categories of PED Rechargeable Batteries

Basic Information, Working Principal and Uses of Different Types of Batteries

Lead-acid battery

The lead-acid battery, invented in 1859 by French chemist Gaston Planté, was the first rechargeable battery to be economically practical. Even if it has been around for a long time, the lead-acid battery is still widely used today because of its low self-discharge rate, big discharge currents, good low-temperature tolerance, and inexpensive cost. Because of their useful features, they may be installed in many different kinds of vehicles, such as automobiles, golf carts, forklifts, and PEDs. The typical components of a lead-acid battery are the anode, the cathode, and the electrolyte, which are represented by Pb, PbO_2, and a concentrated H_2SO_4 aqueous solution, respectively and shown in figure 8 below. Some of the reversible electrochemical reactions that take place in lead-acid batteries has shown below. When the battery is entirely dead, the anode and cathode both change into $PbSO_4$. The electrolyte dissolves most of the H_2SO_4 into water. When fully charged, the cathode is PbO_2 and the anode is Pb. An electrolyte of concentrated H_2SO_4 is used again. In its fully charged state, electrochemistry stores the vast majority of its energy [60].

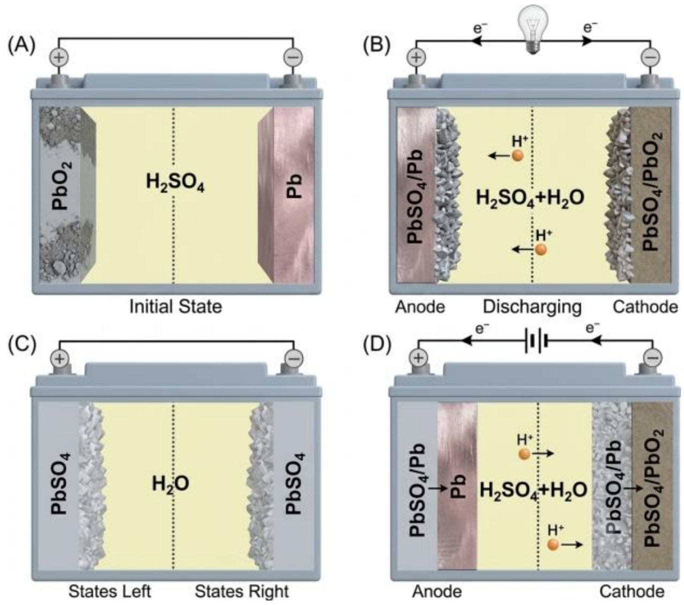

Figure 8: Typical Components of a Lead-Acid Battery (AI generated)

The two most typical forms of lead-acid batteries are cylindrical and prismatic. Two kinds of lead-acid batteries may be distinguished based on the electrolyte immobilization and oxygen recycling capabilities of the battery: sealed lead-acid batteries and valve-regulated lead-acid batteries. The valve-regulated lead acid battery differs from the totally sealed one in that it has a means to relieve any excess internal pressure. In addition, the fumed SiO_2 may be added to the water-based H_2SO_4 solution in the valve-regulated lead-acid battery, or the solution can be absorbed into a porous glass substance. Due to their low capacity, small portable electronic devices (PEDs) like radios often use sealed lead-acid batteries. Charging state (A), discharging process (B), completely discharged state (C), and charge process (D) in lead-acid battery has been shown in figure 9 below. With its higher energy storage capacity, valve-regulated lead-acid batteries are ideal for stationary applications such as telecom power, emergency lighting, and uninterruptible power sources. A valve-regulated battery is also required for powerful portable floodlights. While there are a number of intriguing advantages to using leaky lead-acid batteries, there are also a number of disadvantages, such as a short lifetime (about 300-500 cycles), toxicity to humans and the environment, and subpar charging rates (as shown in Table 1 above). The fact that lead-acid batteries can only store around 40 Wh kg−1 of energy is a major drawback of these batteries. Their specific energy storage capacity is the lowest, and they are often cumbersome and hefty compared to Ni-Cd, Ni-MH, and Li-ion batteries. Because of their low energy storage capacity in relation to their weight, lead-acid batteries aren't a good choice for small PEDs [61,62].

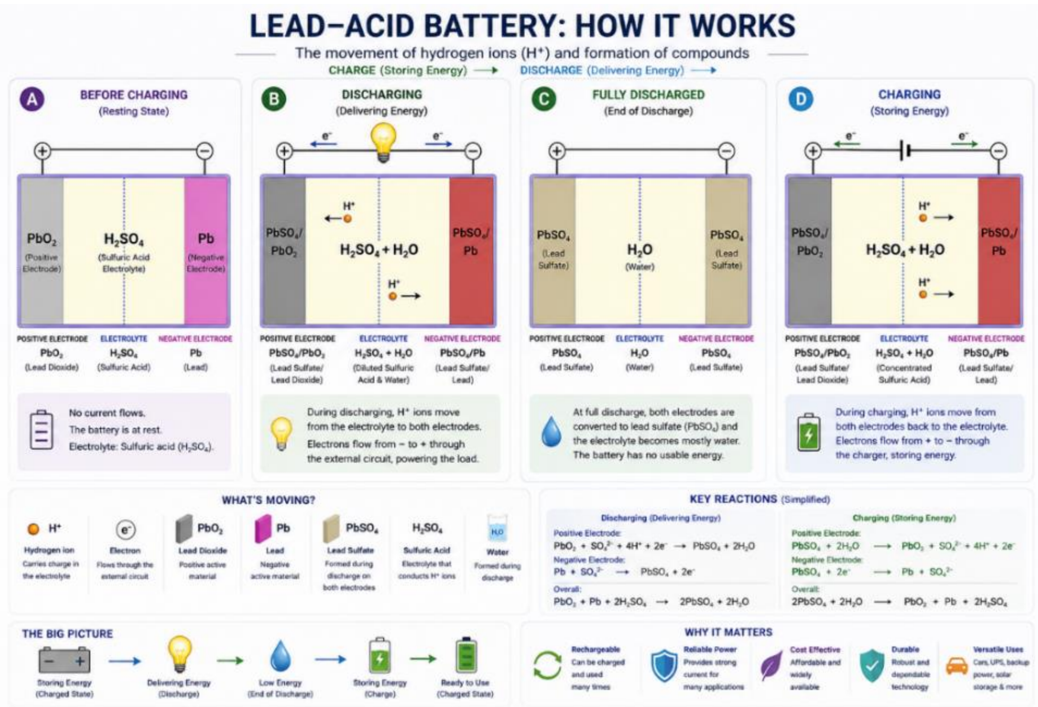

Figure 9: Charging State (A), Discharging Process (B), Completely Discharged State (C), and Charge Process (D) in Lead-Acid Battery (Ai Generated)

Nickel-cadmium battery

The Ni-Cd battery was invented by Waldemar Jungner in 1899. In compared to lead-acid batteries, they offer a variety of advantages, such as a longer lifetime, superior low-temperature performance, quicker charge-discharge rates, and a broad range of sizes (from small sealed portables to massive vented cells). The Ni-Cd battery used to be the go-to for portable and standby power because of these wonderful attributes. Typical components of a Ni-Cd battery, as seen in Figure 10, comprise an alkaline solution (KOH) electrolyte, a cathode made of NiO (OH), and an anode of Cd. Redox reactions between NiO (OH) and Cd are the fundamental building block of the mechanism [63].

Possible Reversible Electrochemical Reactions in A Ni-Cd Battery Include the Following

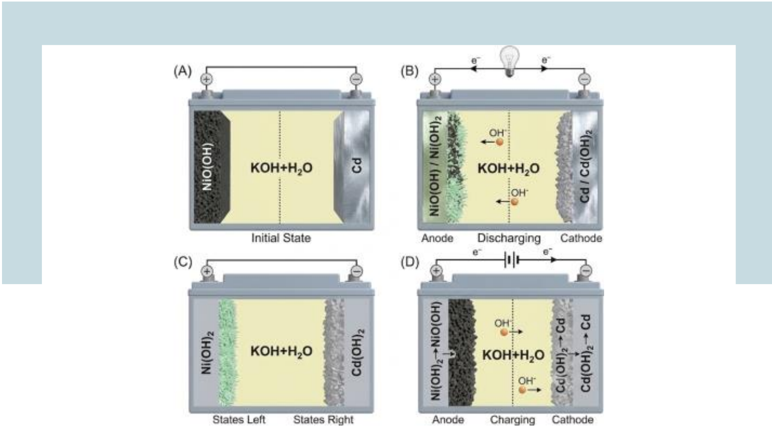

Figure 10: Typical Components of a Ni-Cd Battery (AI Generated)

The first Ni-Cd battery that Jungner created utilized nickel oxide as the cathode and Fe/Cd compounds as the anode. Modern Ni-Cd batteries employ Ni (OH)2 and lead cadmium in their construction. The nickel-cadmium battery was still in its early stages when it was first introduced in 1932. Placing the active battery components inside a porous Ni-plated electrode was a big step forward in 1932. Additional developments, made feasible by collecting gasses created during charging, culminating in the current sealed Ni-Cd battery in 1947. Mass production of these sealed Ni-Cd batteries began in the 1950s. Rechargeable Ni-Cd batteries were commonly utilized in portable electronic devices (PEDs) such as mobile phones, laptop flashlights, video cameras, and radios until the 1990s. There are four possible stages of operation has been shown graphically for the Ni-Cd battery in figure 11 below. The four states are: A fully charged, B while discharged, C after discharged, and D while charged. However, the memory effect is a major drawback of Ni-Cd batteries; these batteries gradually lose part of their maximum energy capacity if they are not fully discharged before being recharged or if they are not used for a long time. Ni-Cd batteries were mostly used in electronic devices like mobile phones due to the fact that these devices are only partially discharged before being recharged. Another issue with Ni-Cd batteries is their high self-discharge rate (as shown in Table 1 above). In addition to being very toxic and expensive, cadmium is a heavy metal. The significant yearly PED disposal rate highlights the potential dangers posed by abandoned Ni-Cd batteries to the environment. Since the 1990s, Ni-Cd batteries have fallen out of favor due to the advent of Ni-MH and Li-ion battery technologies. There are presently just a handful of specialized markets that use Ni-Cd batteries [64].

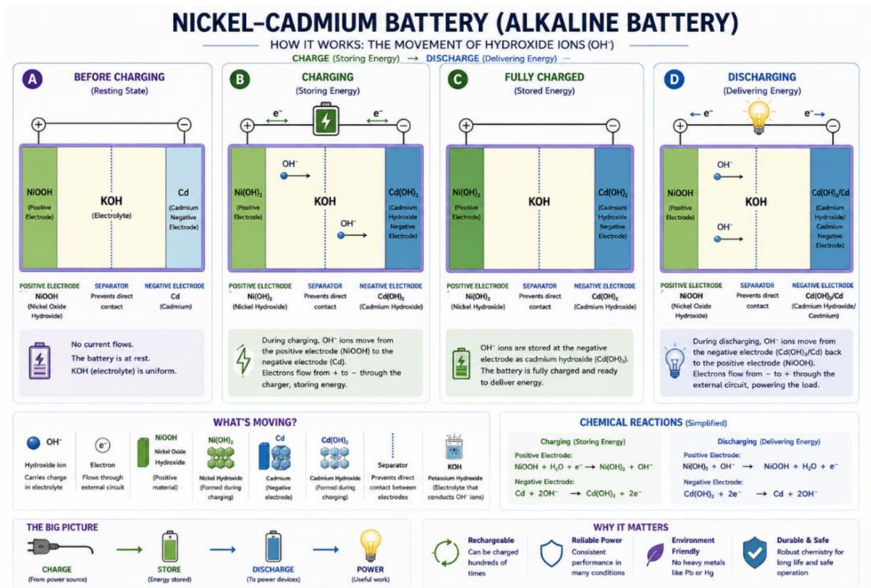

Figure 11: There are Four Possible Stages of Operation Shown Graphically for The Ni-Cd Battery (Ai Generated)

Nickel-metal hydride battery

In 1989, rechargeable Ni-MH batteries were commercially available, and since then, they have become an integral part of many personal electronic gadgets. Its form resembles that of a Ni-Cd battery quite a bit. The anode of a Ni-MH battery is a hydrogen-absorbing alloy instead of Cd, as shown in Figure 12, even though the electrolyte and cathode materials used by both kinds of batteries are identical. Typical components of a Ni- metal hydride battery, has been shown in Figure 12. A schematic of the reversible electrochemistry processes in a Ni-MH battery has been shown below.

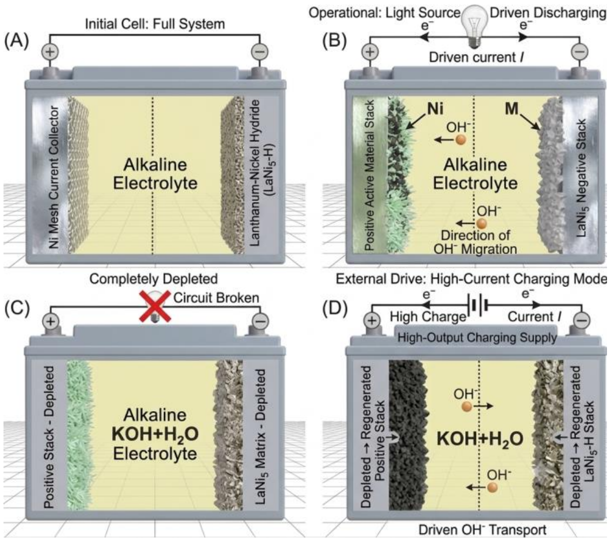

Figure 12: Typical Components of a Nickel-Metal Hydride Battery (Ai Generated)

Due to the replacement of nickel for the metal Cd, Ni-MH batteries are both more cost-effective and less harmful to the environment than Ni-Cd batteries. A reduced memory effect, longer cycle life, greater performance throughout a broader temperature range, quicker charging times, and a higher energy density are just a few of the major advantages that Ni-MH batteries provide over Ni-Cd batteries. They have an energy density that is comparable to lead-acid batteries (nearly twice as high) or Li-ion batteries (half as high as Ni-Cd batteries). The charging state (A), the discharge process (B), the fully discharged condition (C), and the charge process (D) has been shown schematically in figure 13 below. A high-capacity Ni-MH battery may achieve 500 cycles, whereas a low-capacity one can often last over three thousand. A further advantage of the Ni-MH battery is its rapid charging capabilities. Take the one-hour charging time as an example. In the early 1990s, Ni-MH batteries became the main power source for PEDs, replacing Ni-Cd batteries, due to these advantages. The Toyota Prius is only one example of a commercial hybrid electric vehicle that has used Ni-MH batteries. The use of Ni-MH batteries has decreased in recent years due to the pros and cons of Li-ion batteries. Most detrimental of all, Ni-MH batteries have a self-discharge rate that is three times higher than Ni-Cd batteries and much higher than Li-ion and lead-acid batteries. For instance, after only one month, Ni-MH batteries may lose almost a third of their stored energy. As the operating temperature increases, the issue becomes more severe. The high self-discharge rate of daily-charged PEDs may not be a big problem, but for seldom used PEDs, this constraint is a huge one [65].

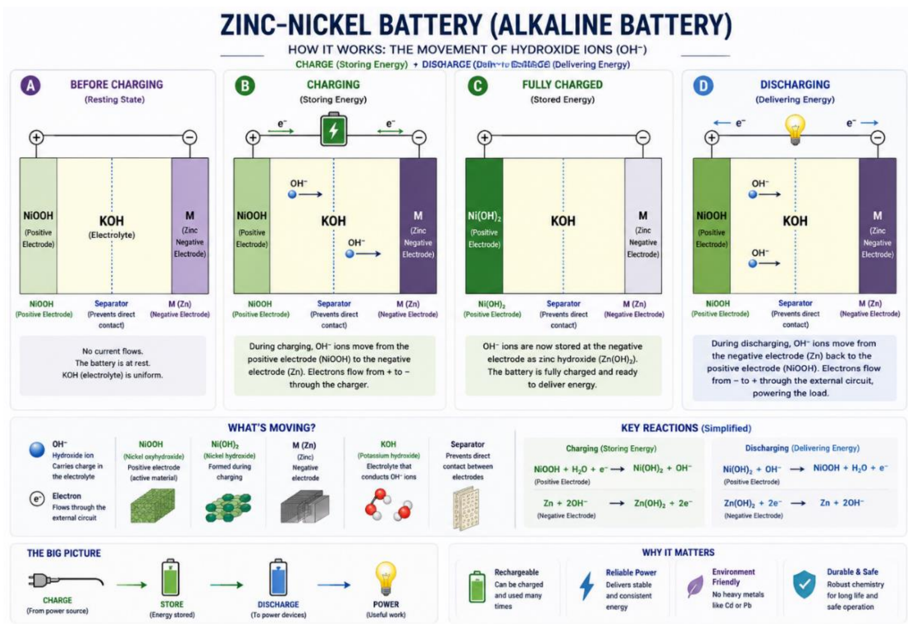

Figure 13: This Ni-Mh Battery Shows the Charging State (A), the Discharge Process (B), the Fully Discharged Condition (C), and the Charge Process (D) Schematically (Ai Generated) [66]

Lithium-ion battery

The introduction of the first lithium-ion battery to the market in 1991 marked the beginning of a new era in personal electronic devices (PEDs), as these batteries quickly became the most popular rechargeable option available. With a high specific energy and typically twice that of standard Ni-Cd batteries—a low self-discharge rate and a high voltage of about 3.6 V and three times that of typical Ni-based batteries and not to mention being maintenance-free, lightweight, safe, and having excellent cycling performance. Their introduction has been incredibly disruptive to the battery industry for many reasons. When it comes to powering PEDs like smartphones, laptops, digital cameras, and more, Li-ion batteries have long since replaced Ni-MH and Ni-Cd. This is due to their many advantages. Concurrently, the need for Li-ion batteries is on the rise due to its use in electric cars, airplanes, and the military. A number of excellent reviews elaborate on the development of Li-ion batteries [67-69].

Figure 14 shows that Li ions move from the anode to the cathode during discharge and then back again during charge. The Li-ion battery's electrochemistry reactions provide the basis of this mechanism. The typical anode component of a lithium-ion battery is graphite or another carbonaceous material. Cobalt oxides, manganese oxides, and lithium iron phosphates are common oxides of lithium that make up cathode components. The liquid electrolytes in traditional Li-ion batteries are Li salts such as Li hexafluorophosphate, Li tetrafluoroborate, or Li perchlorate, which are dissolved in organic solvents such as diethyl carbonate, ethylene carbonate, or dimethyl carbonate. In place of liquid electrolytes, a Li-ion polymer battery employs polymer electrolytes. Lithium salts in a gel with excellent conductivity are a typical polymer electrolyte. It should be emphasized that Li-ion polymer batteries are especially attractive for PEDs, particularly for ultra-slim computers, smartphones, tablets, and wearable electronics, owing to their tiny and customizable construction. To keep things simple going forward, "liquefied Li-ion batteries" will mean Li-ion batteries with liquid electrolytes. Graphite (C) and lithium cobalt oxide (LiCoO2) are used as anode and cathode materials, respectively, to demonstrate the basic chemistry of lithium-ion batteries [70-71].

It is Possible to Turn Back the Clock on the Following Electrochemistry Processes

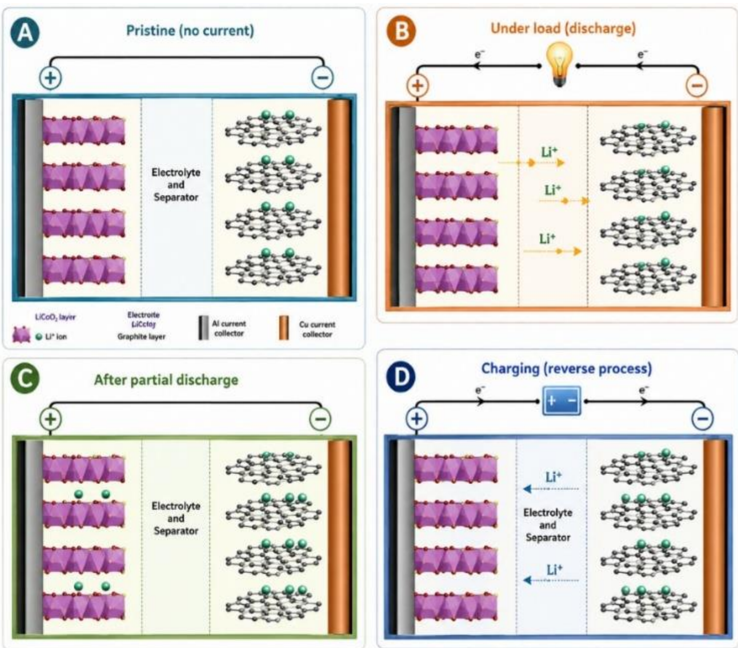

Figure 14: Typical Components of a Lithium-ion Battery (AI generated)

A fully charged state, B the discharge process, C the totally discharged state, and D the charge process in a Li-ion battery has been shown schematically in figure 15 below. With the help of the electrolyte and separator, lithium ions go from the anode, which is graphite, to the cathode, which is LiCoO2. Graphite to LiCoO2 electron transfer is taking place at the same time. Reversing the reaction is part of the charging process. New materials and technology allow Li-ion batteries to steadily increase their power density, longevity, safety, and energy density. Nevertheless, Li-ion batteries do have a few of drawbacks. For instance, the increased manufacturing costs result in higher price when compared to comparable rechargeable batteries. There has been an annual decline in the price of Li-ion batteries, although as shown in above, they are still more costly than competing batteries. In order to restrict voltages and currents and guaranty safe operations, Li-ion batteries need extra protective circuits. There has been a recent uptick in the number of initiatives by the battery industry to find solutions to the problems caused by Li-ion batteries [72,73].

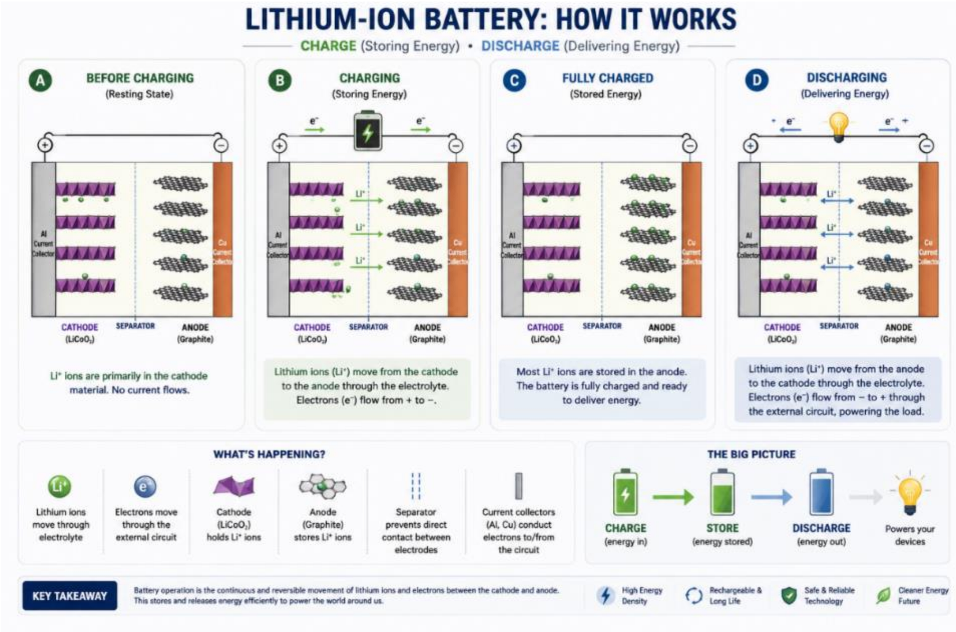

Figure 15: A Fully Charged State, B the Discharge Process, C the Totally Discharged State, and D the Charge Process is Shown Schematically in this Li-Ion Battery (Ai Generated) [74]

Basic Principal and Important Information of Flow Battery

Batteries are categorized into the following five groups as (1) primary batteries, (2) secondary batteries, (3) battery systems for grid-scale energy provision (e.g., flow battery, Sodium-Sulphur battery), (4) fuel cells, and (5) electrochemical capacitors or supercapacitor. A flow battery is an electrochemical conversion device that exploits energy differences in the oxidation states of certain elements (often metals) to store or discharge energy. They are divided into three categories: redox flow batteries, the most common; hybrid flow batteries; and membrane-less flow batteries. Flow batteries get their name from their liquid electrolyte which 'flows' through the battery system, with each category utilizing a different mechanism. A redox flow battery uses a liquid phase reduction-oxidation reaction, hybrid flow batteries have a liquid-solid transition, and membrane-less flow batteries require no electrolyte separation, and are a very new technology. Like Li-ion batteries, within and between each category, flow batteries have different chemistries, including the most commonly used vanadium, and less frequently used zinc-bromine, polysulfide-bromine, iron-chromium, and iron-iron.

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Flow batteries have a liquid electrolyte stored in external tanks rather than in each battery cell (see figure). Since the energy-carrying electrolyte is physically separate from the power-producing stacks, much like an automobile with an internal combustion engine and a separate fuel tank, flow batteries have their energy and power decoupled. If you want a longer duration battery, buy a bigger gas tank, not a bigger gas tank and a bigger engine, which is required in Li-ion batteries. Unlike an automobile with its engine, however, a flow battery can recharge the electrolyte after discharge (have you ever seen an engine run in reverse to produce gasoline and air?). And unlike Li ion batteries, the electrolyte gets charged and discharged by flowing through all the cells and stacks at the same time, so there is one common state of charge (SoC) rather than many individual SoC's for each individual cell. This, in turn, means that cell and stack balancing is not required. Following are the flow battery advantages and disadvantages compared to Li-ion systems.

We need to look to the answer of the question of 'Do flow batteries have lower degradation than Li-ion batteries?' It appears that, in some cases, yes, they do, so long as they are designed and operated in a way that minimizes other contributors to degradation (but many more years of data is needed to prove this definitively). Are they safer? This also seems to be true, since a catastrophic flow battery failure is unlikely to cause a dangerous fire with the associated toxic gases seen in Li-ion failures, but DNV has never tested this. However, managing all the liquid electrolytes is much more difficult in flow batteries and if not contained properly will leak, which is not common in Li-ion systems. Finally, are flow batteries better for long-duration applications (>6 h)? The answer there is still up for debate. Li-ion systems can run for longer by adding more batteries (with the added benefit of more power, if desired), so it comes down to a cost comparison, and only time will tell whether flow batteries can keep up with the rapidly falling costs of Li-ion batteries [75].

Flow battery manufacturers claim that throughput-dependent degradation is very low, giving flow batteries a distinct advantage over Li-ion batteries that degrade more rapidly. The biggest contributor to Li-ion battery degradation is energy throughput or often defined by the number of cycles and that can be confirmed in any testing labs. Test data provided by multiple flow battery manufacturers have suggested that degradation is below that of Li-ion batteries. Time-dependent degradation or calendar fade in flow batteries is near-zero. Some flow battery manufacturers have designed the stack to automatically drain the electrolyte during idle times, significantly reducing time-dependent degradation associated with unwanted chemical reactions between the electrolyte and electrodes. Not all flow batteries have this feature, however, and a drained battery cannot serve any station loads. Flow batteries can increase their energy output (kWh) without increasing their power output (kW), which cannot be done in Li-ion batteries and saves high cost on long-duration or multi-hour applications.

All flow batteries have energy (electrolyte) and battery power (stacks) decoupled, allowing for customization of energy capacity (kWh) at given power or kW. But most flow battery manufacturers only provide a few discrete tank size options rather than unlimited expansion. Also, long-duration applications >4-6 h have not yet proved to have an economic advantage. Flow batteries have a lower fire risk than Li-ion batteries. There is presumably a very low risk of thermal runaway or fire because of a flow battery's non-flammable electrolyte comprised primarily of water. This will likely prevent catastrophic failures seen in Li-ion battery installations. Flow batteries are safer to service than Li-ion batteries. Some flow battery manufacturers/chemistries can discharge the battery stacks to 0 Vdc during maintenance activities with no detriment to the long-term performance of the battery, allowing for safer servicing of the stacks. This is not possible in Li-ion batteries, which cannot discharge to 0 Vdc without permanently damaging the batteries. Even when charged, flow batteries have a low arc-flash risk due to the stack's low DC operating voltage, typically <100 Vdc. This feature, however, is also observed in some Li-ion battery systems that operate at similarly low stack voltages and incorporate a DC-DC converter to achieve higher inverter input voltages [76].

Flow batteries have a complex balance of plant that requires pumps, plumbing, and electrolyte tanks for electrolyte management, which add capital costs and operation and maintenance requirements. Flow batteries do require additional balance of plant equipment to operate, though liquid-cooled Li-ion battery systems require fluid systems with pumps, plumbing, and coolant reservoirs for thermal management. Flow batteries have simpler monitoring and controls and less degradation than Li-ion batteries because no cell-to-cell or stack-to-stack balancing is required. It is true that no cell/stack-balancing requirements are needed in redox flow batteries, since there is a common positive and negative electrolyte across all cells/stacks at a collective SoC, which means no monitoring and control are needed to balance SoC at the cell and stack levels. Hybrid flow batteries, however, have metal plating on one side of the battery, which is like Li-ion battery plating, and therefore require cell and stack balancing. Flow battery system mass is relatively high, which means they are more attractive for stationary applications, where Li-ion systems are more versatile. This appears to be true, with flow battery systems having a lower average gravimetric energy density than Li-ion systems.

Flow batteries have a lower DC round-trip efficiency (RTE) than Li-ion systems. Flow battery RTE is 5%-10% lower than leading Li-ion manufacturers' dc RTE, though ac RTE can be comparable when all parasitic loads are considered. Flow batteries are far behind Li-ion batteries in market penetration and diversity of markets. Li-ion batteries dominate the energy storage market and have vastly higher market share and are integrated into a wider range of commercial products. Market opportunities may arise that favor attributes of flow batteries, but Li-ion will be competing to expand to future applications as well. Flow batteries have a more accurate measurement of SoC, allowing for a wider operating range of the battery and less degradation than Li-ion batteries. Some flow battery manufacturers use a reference call to continuously measure the open circuit voltage directly even when the stacks are under load, providing a more accurate and continuous method of calculating SoC than Li-ion batteries that use an inferred method that compares voltage and current measured under load.

Finally, not all flow battery technology is equal. Vanadium-based technology is the most mature, with the first commercial system installed in the mid-1990's. Many other technologies have far less development and almost no field data to speak of. Differences in design and electrolyte chemistry also may affect performance. Redox flow batteries like vanadium and polysulfide bromide, and which all have chemical reactions within the liquid phase, may prove to have advantage over hybrid flow batteries like zinc-bromine, zinc-cerium, zinc-iron, iron-iron. And which have a liquid-solid electrochemical reaction prone to additional degradation due to dendrite formation and increased resistance. Again, certain chemistries require electrolyte conditioning, a process of balancing the electrolyte chemistry using additional hardware or maintenance steps, which is required daily in many flow battery systems. Moreover, certain flow battery manufacturers have focused heavily on design for manufacturability, minimizing install time, reducing O&M, and integrating with renewable resources like wind and solar, which may give them a cost advantage upfront and over the life of the system. Flow battery system costs drop through modular stack designs, decoupled power-energy scaling, and low maintenance requirements. Upfront capital expenses remain high compared to lithium-ion, but long operational lifespans improve overall lifecycle value for renewables [77].

Major Performance Parameters

As battery performance depends on temperature, SoC, and battery age, it is essential to measure or estimate these properties to ensure full vehicle functionality, implement measures to keep the battery within its optimal operating window, and enable early detection of limited battery functionality for replacement strategies. Advantages and disadvantages of different types of batteries has been shown in table 2 below. Battery monitoring enables electrical power management that may include both reducing electrical consumption by limiting operable luxury applications and increasing power generation through appropriate control of alternator, idle speed and automatic gearbox control [78,79].

- Energy density Lithium-ion batteries typically have a power density of 150 to 200 Wh/kg, making them excellent for use in products that demand a reduction in weight. These products include electric vehicles (EVs), smartphones, and laptops. Due to their high energy density, lithium-ion batteries store more energy per unit weight, making them ideal for portable devices and applications requiring extended operation [80].
- Charge and discharge efficiency Lithium-ion batteries have a charge and discharge efficiency of more than 90%, which is why they are commonly employed in electronic products and electric cars. The excellent charge and discharge performance minimizes energy loss throughout the conversion process, making it perfect for systems that operate for a long time or require efficient energy storage, including solar energy storage systems and electric automobiles. Its high efficiency enables more energy to be used per charge, extending the device's lifespan [81].
- Energy storage cost. The cost of producing lithium-ion batteries has decreased dramatically in recent years, with a current cost of approximately $137 per kilowatt-hour. With advancements in manufacturing techniques and savings in production, this cost is predicted to continue to fall in the next few years, approaching $100/kWh [82].
- Cycle life. Lithium-ion batteries typically have 500 to 1,500 charge and drain cycles, and in some outstanding performance applications, optimized batteries can have a cycle life of over 3,000times [83].
- Charge and discharge speed. The charging and discharging rates of lithium-ion batteries can be measured using the C-rate. Its rapid charge and discharge rate enable it to finish charging quickly, which is critical for everyday electronics like mobile phones and laptop computers. Furthermore, with the adoption of fast-changing technology, the speed of charging of lithium-ion batteries is constantly improving, lowering users' wait times. However, high charge and discharge rates can shorten battery life, they are typically managed by battery management software (BMS) [84].
- The cost of lithium-ion batteries has been decreasing over time and is now around US$100 per kWh. As global demand for sustainable energy and electric vehicles grows, lithium-ion battery production expands, resulting in lower unit costs.

Battery Type	**Advantages**	Disadvantages
Advantages	Disadvantages	
Lead-acid	i) Mature technology ii) Word wide production iii) Low material cost iv) No memory effect v) Relatively low self-discharge rate vi) Relatively low capital cost	i) Short cycle life ii) Modest energy/power density iii) Long charging time iv) Safety issues (gas discharge) v) Temperature sensitive output vi) Poor reliability
Lithium-ion (Li-ion)	i) Long cycle life ii) High round trip efficiency iii) Global R&D efforts iv) Relatively fast charging v) Highly reliable vi) Low discharge rates vii) Excellent energy/power density	i) High capital cost ii) Safety issues (Thermal runaway) iii) Material bottle concerns iv) Poor recovery/recycling v) Advanced battery management systems required
Nickel metal hydride (NiMH)	i) Modest initial cost ii) Acceptable energy/power density iii) Modest round-trip efficiency iv) Highly reliable v) Excellent safety record vi) Relatively fast charging	i) Higher self-discharge rate ii) Memory effect iii) Relatively short cycle life iv) Poor recovery/recycling

Table 2: Advantages and Disadvantages of Different Types of Batteries

Challenges of Lithium-ion Batteries

Technical Challenges

- **Security Issues** A major safety risk for batteries made with lithium-ion is "thermal runaway," which occurs when the battery is subjected to high temperatures, charging too much, or physical damage, and the chemical reactions inside the battery become uncontrollable, causing the internal temperature to rapidly rise and cause a fire or explosion. Because of the enormous amount of energy stored in high-energy-density battery packs, such as those used in electric vehicles, the risk of thermal runaway is very high. When the temperature inside the battery exceeds a critical threshold, the electrolyte may decompose and release flammable gases, increasing the risk of a fire [85].
- **Longevity:** Lithium-ion batteries have a limited life cycle, and when they are charged and discharged repeatedly, their ability steadily declines. This phenomenon is commonly known as "capacity fading" or "battery ageing." After several hundred cycles, a battery may only deliver a percentage of its first capacity, reducing the device's longevity

[86].

- **Environmental impact issues:** Lithium-ion batteries require a considerable number of rare metals, including lithium, cobalt, and nickel. The extraction of these metals has a significant impact on the environment. For example, cobalt mining is mostly centred in the Democratic Republic of Congo, which includes issues such as environmental pollution, ecological degradation, and human rights violations [87].
- **Cost challenge:** Although the cost of batteries made from lithium-ion has been falling year after year in recent years, production costs stay high, particularly in large-scale applications such as electric vehicles and energy storage systems on a massive scale. Manufacturing lithium-ion batteries requires the use of high-purity elements such as cobalt, lithium, and nickel, as well as sophisticated production procedures and stringent quality control, all of which raise manufacturing costs [88].

Security Challenges

- **Solid-state Batteries:** Solid electrolytes provide stronger thermal stability than standard liquid electrolytes, which can considerably reduce the danger of thermal runaway in the battery. Solid-state batteries not only lower the combustible gases emitted during electrolyte decomposition, but they also boost the battery's energy density [89].
- **New Diaphragm Technology:** Higher-temperature stable separating materials can improve the reliability of the battery's inner workings and keep it from short-circuiting or failing at elevated temperatures. Ceramic separators, for example, have gradually gained popularity as a safety upgrade for lithium-ion batteries because of their exceptional thermal stability [90].
- **Battery Management System (BMS):** A sophisticated BMS may track temperature, current, voltage, and other battery characteristics in real time to prevent overcharging, over-discharging, and overheating, thereby reducing the risk of thermal runaway. By intelligently changing the charging and discharging rates, BMS can delay the onset of thermal runaway.
- **Development trend:** Solid-state batteries are seen as the future of lithium-ion battery safety. Solid-state battery technology is predicted to enter commercial production over the next ten years, with widespread use in electric vehicles, energy storage systems, and other applications. In addition, innovative nanomaterials, coating technologies, and automated monitoring systems will improve the safety of lithium batteries.

Lifespan Challenge

- **Type Electrode Material:** Researchers are aiming to create new silicon-based or lithium metal anodes with increased ability and cycle stability. By enhancing the structure of the materials used for electrodes, the mechanical stress generated by the intercalation and deintercalation of the lithium ions can be decreased, extending the battery's service life.
- **Electrolyte improvements:** High-stability electrolyte additions can prevent electrolyte decomposition under high-pressure, high-temperature circumstances while avoiding adverse reactions. The inclusion of additives (for instance, fluorinated electrolyte) can considerably increase the battery's cycle stability and delay capacity degradation.
- **Smart charging technology:** Optimizing the process of the charging algorithm and using advanced charging technology can help to reduce battery damage during charging and discharging. For example, several electric car manufacturers have begun using rapid-charging technologies and segmented charging algorithms to alleviate battery stress during deep draining and quick charging.
- **Development trend:** The lifespan of batteries made with lithium-ion will be extended further as battery material research advances, and the battery's cycle life may eventually exceed 3,000 cycles. At the same time, solid-state batteries are projected to play an important role in prolonging battery life due to their superior electrochemical stability. As the need for long-life batteries in electric automobiles and energy storage increases, research into improving battery life will become more important [91].

Environmental Impact Issues

- **Material Recycling Technology:** To lessen dependency on rare metals, batteries recycling equipment is fast evolving. Recycling lithium, cobalt, nickel, and other metals from old batteries reduces demand for new natural resources and lowers the environmental impact of mining. Closed-loop recycling technology may significantly boost metal recycling efficiency while lowering the environmental impact of battery production.
- **Material Substitution:** Some research aims to build cobalt-free batteries with lithium-ion or replace rare elements with more abundant minerals like iron and sodium. Because of the abundance of sodium, sodium-ion batteries have appeared as a potentially practical alternative to lithium batteries. In addition, the use of cobalt-free battery packs, such as iron phosphate lithium power sources, is growing, particularly in sectors where great energy density is not required.
- **Environmentally Friendly Material Development:** The study and development of some novel materials is geared to minimizing environmental pollution. Water-based electrolytes, for example, are considered more environmentally benign than standard organic solvents. Furthermore, the research on compostable battery materials is steadily progressing to prevent environmental contamination following battery disposal.
- **Development Trend:** As global environmental restrictions tighten, battery longevity will become a major focus for future improvements. Battery recycling technology is likely to advance significantly in the next few years, and closed-loop logistics systems will become more widespread in the battery manufacturing industry. At the same time, the creation of green manufacturing processes and alternative resources will become a priority for the sector.

Cost Challenge

- **Scale effect and production process optimization:** As the volume of lithium-ion batteries produced grows, manufacturers can save costs by improving efficiency in production and perfecting procedures. For example, automated lines of production, modern manufacturing technologies (including 3D printed electrodes), and optimized production procedures can all help to cut production costs on a big scale.
- **Material substitution and reducing dependence on rare metals:** One important strategy for lowering battery prices is to limit the consumption of rare metals like cobalt and nickel. Lithium iron phosphate (LFP) batteries have emerged as the preferred low-cost option due to their lack of cobalt and nickel and their low material costs. Future material developments, such as sodium-ion batteries, are predicted to dramatically reduce battery production costs.
- **Government Subsidies and Policy Support:** Some countries and regions encourage the use of electric motor vehicles and systems to store energy through government funding or tax breaks, hence boosting the growth of the lithium battery industrial chain. Furthermore, the National Strategy Reserve Program may help stabilize price variations in essential metals such as cobalt and lithium, thereby lowering the long-term expense of batteries.
- **Development Trend:** The cost of producing lithium-ion batteries is likely to reduce further in the coming years, driven mostly by worldwide demand for electric motor vehicles and renewable energy storage devices. With material innovation, improved production efficiency, and greater economies of scale, the cost of lithium-ion batteries is predicted to approach the critical threshold of $100/kWh, further driving their use in a variety of situations [92].

Policy of Power Generation and Policy

Power generation is one industrial sector with a major contribution to greenhouse gas emissions (mainly CO_2). For climate change mitigation, special attention is given to the reduction of CO_2 emissions by applying carbon capture and storage (CCS) techniques. CCS technologies refer to a broad range of methods to allow CO_2 emissions to be captured and then transported to safe geological storage (e.g. saline aquifers, depleted gas and oil fields, EOR etc.), rather than being emitted into the atmosphere. CCS technologies are expected to play a significant role in the future for curbing greenhouse gas emissions and for sustainable development. Power generation or electricity generation is the process of generating electric power from sources of primary energy such as heat (thermal), wind, solar, and chemical energy. Overcoming challenges and improving operations in power generation begins with understanding your data. You need to capture, store, contextualize, and visualize time-series information and make it available to the right people at the right time to enable the right decisions. Many operators in the power generation industry are increasingly looking to move toward a data-driven and technology-enabled way of working. Often this is called the Manufacturing 4.0 or Plant 4.0. Household energy storage policies in major countries around the world has been shown in brief in table 3 below.

Household energy storage policies in major countries around the world		
Nation	**Tax deduction**	**Subsidy amount**
Germany	Starting from 2023, power generation income tax and 19% VAT will be exempted nationwide.	Some areas such as Berlin still have energy storage subsidies (300 euros/kWh in Berlin).
Italy		Provides an income tax credit of 110% of the installation cost, which will gradually decrease starting in 2023.
Austria	Stop collecting self-use tax on photovoltaic power generation (if the cumulative self-produced power exceeds 25kWh, it will be paid at a rate of 0.015 euros/kWh)	A new allocation of 40 million euros will be allocated in June 2022 for photovoltaic installations less than 10kW, with subsidies up to 285 euros/kW.
U.K.	Optical storage installation is exempt from VAT	
Sweden	Devices below 500kW are exempt from energy tax (approximately 3.3-euro cents/kWh)	In 2021, 260 million Swedish krona (approximately 24 million euros) will be allocated to subsidize 10%-20% of the purchase cost of rooftop solar storage.
Spain	Stop collecting photovoltaic power generation self-use tax (7%), and reduce income tax by up to 20% of the purchase cost	Assistance subsidies for renewable new energy in 2021 are 1.32 billion euros; of which 220 million euros are for energy storage subsidies, and households can receive a 70% credit for energy storage purchase costs
Poland	VAT is reduced from 23% to 8%, and the purchase cost is deductible from income tax, up to PLN 53,000 (€11,000)	Household savings provide a one-time subsidy of 50% of the purchase cost. In December 2022, the maximum subsidy limit will be increased from PLN 7,500 (EUR 1,590) to PLN 16,000 (EUR 3,400).
Netherlands	On January 1, 2022, some double taxation of consumption tax and production tax on energy storage systems will be stopped.	
USA	For energy storage systems above 5kWh, investment tax relief of up to 30% will be granted until 2026	California SGIP subsidizes according to capacity and duration, with full subsidies within 2MWh, continuing until 2026

Japan		The Ministry of Economy, Trade and Industry has invested approximately US$98.3 million to provide 66% cost subsidies for households and businesses that install lithium-ion batteries.
Australia		The battery energy storage support program provides subsidies on a proportional basis. Holders of preferential cards can enjoy a subsidy of US$600/kW, and others can enjoy a subsidy of US$500/kW. 5/10 kWh batteries can receive subsidies of up to $3000/6000.

Table 3: Household Energy Storage Policies in Major Countries Around the World [94]

Although in principle, this may sound relatively straightforward, the reality is that things have become a lot more complicated since companies deployed their initial plant control systems and operations-based information technology solutions years ago. Organizations face many challenges of scale and performance, data quality, data silos, integration, and cybersecurity. There is also an increasing number of confusing and conflicting messages within the industry about how best to support digital operations to enable further automation and advanced "Big Data" predictive analysis. Most companies are trying to evaluate how the new "digital" approach fits and how techniques like machine learning, artificial intelligence, and advanced statistics can improve the performance of plants and operation supply chains. It is not that modelling, simulation, and automation projects are something new to power generation, but the industry has been implementing these techniques and technologies for many years. What is different is that the Plant 4.0 is more instrumented and more connected than ever before. With this degree of digitization, operators can develop data-driven models that combine physics, statistics, and best practice engineering principles in order to gain greater insight into what is going on in the plant, and how they can improve performance of the total asset lifecycle.

Perspectives of Lithium Salts and Beyond

The increasing need for energy storage has motivated intensive research on batteries with different chemistries in recent years. Among the elements of the batteries, the salts and their solvent play an important role. In particular, the cathodic stability at low potential depends importantly on the choice of the cation, while the stability at high potentials is mainly due to oxidation of anions and the ion mobility and dissociation depend primarily on the delocalization of the anion, so that many attempts are made to find the optimum choice of both the cations and anions of the salts, and their solvents. Although lithium-based batteries are almost exclusively used today, efforts are currently made to explore batteries based on sodium, aluminum, magnesium, calcium, and potassium.

The rapid transition from fossil fuels to green energy was endorsed at the political level by the Paris Agreement to address climate change. The increased average economic growth rate is concomitant with an increase in electricity consumption per capita. In addition, the population on Earth is increasing very rapidly. When applied to the present situation, we know that chain reactions leading to a first-order transition result in a shortage of electricity and force a drastic change in lifestyle. The challenge for scientists and technologists is to propose solutions to avoid this first-order transition. The solution will not be unique, but will requires a variety of energy sources like geothermal, biomass, hydroelectricity, etc. and energy storage will play an increasing role. Different kinds of energy storage systems are used at different levels to manage the electricity supply from the GWh scale down to the kWh used by consumers [96,97].

The most fundamental relationship in the operation of batteries is that for every ampere that flows over a period of time, a corresponding chemical reaction or other change must occur. The extent of this change is dependent on the molecular weight and the electronic structure of the elements taking part in the battery current-producing reaction. Other secondary reactions may also occur, but there must be a primary pair of theoretically reversible reactions for electricity to be produced. The power produced by a battery is measured by the number of amperes produced multiplied by the time of operation multiplied by the average voltage over that time.

Energy storage systems vary widely in performance, with pumped hydro offering the lowest cost and longest life for grid-scale, lithium-ion leading in fast-response efficiency, and flow batteries excelling in flexible long-duration storage despite higher capital outlays. Lithium-ion batteries dominate short-duration grid and commercial power storage, while flow batteries are emerging as an alternative for long-duration energy storage that can scale capacity safely by using separate liquid electrolyte tanks. Attention is also focused on rechargeable batteries, which constitute a market in exponential growth that has major demand for portable use, electric cars, and large-scale energy storage to solve the problems with intermittent electricity production by windmills and solar plants. Today, lithium batteries are almost exclusively used for this type of energy storage, while flow batteries are being tested. Na/S and $Na/NiCl_2$ batteries operating at 300°C are developing slowly after a major incident. In parallel with the research on these batteries to improve their performance and safety, new efforts are underway to identify alternatives to lithium. In particular, recent progress on more abundant sodium, magnesium, aluminum and potassium batteries, as well as lithium-sulfur chemistry, is receiving significant attention. Review papers on these advanced batteries are available. However, these reviews usually focus on a particular battery system, a pattern justified by the large number of publications. For example, in 2016, more than 900 research papers were published on Li-S batteries only.

There are numerous reviews on the different components utilized as electrode materials in advanced batteries, with a lesser number on separators. Only a few reviews are devoted to the electrolyte. All the aspects of the electrolyte have been reviewed, but usually the reviews focus on the additives chosen to improve the safety or control the solid-electrolyte interface (SEI). In addition, the salts used in the electrolyte are very important as they ensure the ionic conductivity and the stability window, but this has not been a major topic of many reviews so far. These considerations guided us to the present work, which focuses on the electrolyte salts used in the different battery chemistries mentioned here. Every battery chemistry has its advantages and disadvantages due to the different elements that are used. The salts are effective depending on their concentration and the type of solvent in the electrolyte, because the electrolyte interacts with the electrodes via SEI formation and the insertion or not-insertion of anions or cations into the electrodes.

However, the separator plays a role in battery safety and may also be functionalized to prevent internal shuttling in Li-S batteries, for example. Therefore, battery performance depends on the compatibility between all the components. Nevertheless, a review focusing on the salts relative to the solvents is timely, and a discussion of their applications in various advanced batteries is useful. One reason is that the performance of a battery is due to the ions in the electrolyte, and the behavior of anions in different batteries are often the same, As example: (1) ion mobility and dissociation depend primarily on the delocalization of the anion; (2) carbon is commonly used as the active electrode component, so the interaction and insertion properties of this anion towards carbon is similar in many batteries; (3) electrolyte conductivity also depends on salt concentration, which usually shows a maximum at 1 M salt, a compromise between viscosity and concentration of the charge carriers and is optimized to achieve the best conductivity and/or electrochemical properties.

Salts in Li-ion and Na-ion Batteries

The salt used in commercial Li-ion batteries is almost exclusively lithium hexafluorophosphate ($LiPF_6$), because its solutions in dipolar aprotic organic solvents, either cyclic carbonates like ethylene carbonate or linear carbonates like dimethyl-, diethyl-, and ethyl-methyl carbonate and show high ionic conductivities, good electrochemical stability, and protect the Al current collector against corrosion. There are several drawbacks. First, it has thermal stability above 55 °C. On the other hand, the studies of Na-ion batteries (SiBs) are taking place in parallel with those of Li-ion batteries. The Li-ion battery dominates the market today because of its high-rate capability and energy density. Sodium is abundant and a low-cost element for energy storage devices but has a propensity for dendrite formation. Some reviews on Na batteries have addressed the electrolytes, for example, non-aqueous electrolytes, while other reviews discussed aqueous liquid electrolytes.

Magnesium Salts

Magnesium batteries are very attractive despite the lower theoretical capacity of Mg, 2061 $mA\,h\,cm^{-3}$, than that of lithium (3862 $mA\,h\,cm^{-3}$). Magnesium has several advantages over lithium as Mg is abundant and much cheaper than Li, Mg is not prone to dendrite formation, Mg is more stable than lithium in air. The major problem with Mg remains the lack of a suitable solvent-electrolyte combination, because the SEI formed at the Mg surface in common electrolytes blocks ion transport.

Aluminum Batteries

Research on rechargeable Al-ion batteries has been underway for about 30 years. These batteries are attractive because of their potentially high energy density due to the redox reaction $Al^{3+} <=> Al^0$ involving three electrons. In addition, aluminum is abundant and very low-cost. However, Al-ion batteries have encountered technical problems such as poor cycle life and significant capacity fade.

Calcium Salts

Calcium is almost disqualified as an electrode because of its high reactivity due to its strong reducing power and high solubility in molten salts, but the feasibility of plating/stripping was proven by Ponrouch et al. using the salt mixture Ca $(ClO_4)_2$ and Ca $(BF_4)_2$, in EC: PC solvent in a cell at 100 °C. Therefore, instead of Ca metal alone, secondary batteries were constructed with solid calcium alloy negative electrodes (Ca-Al, Ca-Mg, Ca-Si).

Potassium Salts

Potassium has recently emerged as a potential vector element for secondary batteries. With a melting point of 63.5 °C the temperature span of a K electrode is reduced. Like calcium, potassium is cheap and abundant, but it is also reactive with the electrolyte components, so a SEI is needed to stabilize the interface, and until recently, it was a challenge to obtain good capacity retention with cycling. K+ intercalates in graphite to KC_8. It is difficult to find a cathode in which K+ ions.

Ultimately, Lithium-ion and lithium-metal polymer batteries are still the best choice for plug-in EVs. However, Li-S batteries are reaching the market, with some companies (Oxis, Sion power) reporting 400 $Wh\,kg^{-1}$ cells. The advantage of Li-S over Li-ion batteries is the gravimetric energy density. However, the volumetric energy density is lower for Li-S batteries, and is expected to stay lower in the next few years. The initial application of Li-S batteries in transportation should be in electric. If we look for an assessment of the various salts that are in use or are considered for such in new battery systems. It is certainly impossible to separate this component from the solvent, liquid or solid which together constitute the electrolyte. In turn, each electrolyte is designed to allow a smooth operation of both electrodes with safety included, in a variety of environments and chemistries. This work reflects this complexity.

Recommendations

Modern battery manufacturing processes should emphasize pursuing a few distinct goals. Effort needs to be taken to accelerate the development of new cell designs in terms of performance, efficiency, and sustainability. Enhancing Multiphysics models by incorporating the critical formation and ageing steps and alleviating the computational burden through the implementation of ML algorithms or reduced-order methods would facilitate the development of more accurate and efficient tools. Even coupling these models with advanced optimization algorithms within AI frameworks would accelerate the inverse design of electrodes and cells. Again, an attempt should be made to close the loop between cell design and cell manufacturing development, where the cell performance and ageing aspects should be considered prior to the manufacturing phase, through a holistic digital twin covering the whole battery cell manufacturing chain, from materials to cell usage conditions. Additionally, effort needs to be taken to accelerate the optimization of existing and future manufacturing processes in terms of cell chemistry, manufacturing costs, and sustainability/environmental impact by building computationally efficient and accurate digital twins of the manufacturing process. Lastly, an effort needs to be taken to accelerate the development of additive manufacturing for the rapid near-industry production of battery cell prototypes and for the production of 3D structures of the electrodes.

Battery storage power stations use rechargeable batteries for load-leveling to storing electric energy at times of low demand for use during peak periods and for renewable energy uses like storing power generated from photovoltaic arrays during the day to be used at night. Load-leveling reduces the maximum power which a plant must be able to generate, reducing capital cost and the need for peaking power plants. According to a recent report from Research and Markets, the global battery market is accelerating at an unprecedented pace. According to a report published by Research and Markets in December' 2024, the industry is projected to reach a staggering USD 329.84 billion by 2030, growing at a CAGR of 16.4% from 2025. At the heart of this transformation lies the lithium-ion battery. With a 44% market share in 2024, lithium-ion remains the technology of choice for EVs, consumer electronics, and BESS. Much of this momentum is driven by the EV revolution, rising energy storage needs, and the global push towards net zero. Small rechargeable batteries can power portable electronic devices, power tools, appliances, and so on. Heavy-duty batteries power electric vehicles, ranging from scooters to locomotives and ships. They are used in distributed electricity generation and in stand-alone power systems.

As sustainability becomes a core pillar of the battery value chain, the market is witnessing a marked shift toward circularity. From policy frameworks to industrial innovation, battery recycling is emerging as a key enabler of long-term growth – underscoring a broader movement to reduce reliance on virgin materials and minimize waste. With increased public and regulatory scrutiny around battery safety, pollution and fire hazards, companies are turning to advanced lithium-ion battery recycling solutions as a means of mitigating risk and contributing to a greener future. It is no longer just a matter of environmental responsibility. And it's becoming an operational imperative. There are few key dynamics are fueling the rise of lithium-ion battery recycling. In 21st century, with the automotive sector accounting for 31% of battery market revenues in 2024, EV adoption is significantly shaping demand for both battery production and recycling. The global transition away from internal combustion engines highlights the critical need for domestic recycling infrastructure to manage the incoming wave of end-of-life EV batteries. On the other hand, as grid systems incorporate more solar and wind power, reliable energy storage becomes essential. Lithium-ion batteries are central to this effort – but without efficient recycling, the sustainability of these systems is compromised. Additionally, there is a raw material scarcity in rechargeable battery manufacturing. So, with global attention on the ethical and environmental costs of mining lithium, cobalt, and nickel, battery recycling offers a sustainable pathway to recover and reuse these valuable resources.

Conclusion

Energy-storage technologies have rapidly developed under the impetus of carbon-neutrality goals, gradually becoming a crucial driver of the energy transition. Electrochemical energy storage is a leading sustainable technology, relying on systems such as lithium-ion batteries, flow batteries, and supercapacitors to store energy efficiently. It stands out among mechanical, thermal, and chemical methods for its high flexibility and direct conversion capabilities. As more renewable energy is developed, energy storage is increasingly important and attractive, especially grid-scale electrical energy storage; hence, finding and implementing cost-effective and sustainable energy storage and conversion systems is vital. Batteries of various types and sizes are considered one of the most suitable approaches to store energy, and extensive research exists for different technologies and applications of batteries; however, the environmental impacts of large-scale battery use remain a major challenge that requires further study.

Battery energy storage is reviewed from a variety of aspects such as specifications, advantages, limitations, and environmental concerns; however, an important point is the environmental impacts of batteries on people and the planet. Batteries are the most common and efficient storage method for all small-scale power needs, and vast numbers of batteries of different types and sizes are manufactured annually; this will grow as the population and demand for portable electronic devices grow. The future growth of lithium-ion batteries confronts many hurdles, including safety, longevity, environmental impact, and cost. However, with advances in materials science, the adoption of modern technologies, and improvements in the global industrial chain, lithium battery performance and sustainability are likely to improve dramatically in the future. Innovative advancements such as solid-state batteries, renewable energy sources, and smart charging technology will encourage the widespread use of lithium-based batteries in electric vehicles, energy storage, and personal gadgets.

Batteries may impact the environment during manufacturing, use, storage, treatment, disposal and recycling. Due to their vast range of applications, a large number of batteries of different types and sizes are produced globally, leading to different environmental and public health issues. After several hundred years of development, battery technology has become a key factor for large parts of modern industry. Today, large-scale applications powered by electrochemical storage systems are being considered. To keep pace with the accelerated introduction of battery electric vehicles, stationary storage systems, and new mobile devices, it is necessary to establish new approaches to research and development in the battery sector. Not only is the number increasing, but so is the demand for better performance of storage devices. These should have more energy and performance, and be manufactured on a sustainable material basis. They should also be safer and more cost-effective and should already consider end-of-life aspects and recycling in the design. Therefore, it is necessary to accelerate the further development of new and improved battery chemistries and cells.

In this high-tech era, sustainability and eco-friendly material, system and technology are few of the key issues in rechargeable battery development. Rechargeable batteries already play a vital role in many sustainable solutions, like energy storage or electric mobility and flexibility. Though, as we know battery itself contain harmful and toxic materials. In 21st century, AI and ML can help us develop new, sustainable alternative materials. For example, current research explores new battery solutions, raw materials, or biobased materials. Again, AI and ML can aid in the characterization, classification, design, and processing of these materials to decrease their time to market. Additionally, we can also use AI and ML to link materials research to the circular economy or to battery recycling to obtain materials from old batteries, or to optimize challenging extraction processes. It needs industry and academia collaboration. Today, few companies and researchers' group have already developed AI tools for many application areas and which will develop further in near future. As we also know that, AI in Atmospheric Science and AI for Sustainability are well known to many relevant stake-holders. Actually, this is the right for AI and smart technology in rechargeable battery research. Today rechargeable batteries are a hot topic in the search for sustainable solutions, and materials research is one of the focus areas. AI and ML can help us to raise the bar of battery materials research on global level.

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